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DERIVATION
OF JET-AIRCRAFT
CONTRAIL-FORMATION CURVES

Herbert S. Appleman

JANUARY 1957

UNITED STATES AIR FORCE

AWS TECHNICAL REPORT
No. 105-145

HEADQUARTERS
AIR WEATHER SERVICE
MILITARY AIR TRANSPORT SERVICE
UNITED STATES AIR FORCE
Washington 25, D. C.
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FOREWORD

1. <u>Purpose.</u> To present the data and calculations on which <u>AWS Manual 105-100 (Rev.)</u>, August 1956, was based.

2. <u>Scope.</u> The assumptions, calculations, tables, and graphs used in deriving the contrail-formation curves and procedures in the original edition of <u>AWSM 105-100</u> (April 1952) are reviewed and revised in this Report in light of more recent data, particularly from Project Cloud Trail. New tables and graphs are presented which were used as the basis for the revision of <u>AWSM 105-100</u> issued in August 1956. This Report will be of particular interest to field activities engaged in verifying the procedures in <u>AWSM 105-100</u> or in adapting them to conditions in overseas areas. For all practical purposes <u>AWS TR's 105-103</u> and <u>105-112</u> are made obsolete by this Report and will no longer be stocked; they can still be obtained from ASTIA if desired by research activities.

3. <u>Additional Copies.</u> This Report is stocked at Headquarters MATS, Command Adjutant, Publishing Division. Additional copies may be requisitioned from Headquarters Air Weather Service, ATTN: AWSAD, in accordance with AWSR 5-3, as amended.

Approved:

Robert D. Fletcher

ROBERT D. FLETCHER
Director, Scientific Services

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DERIVATION OF JET-AIRCRAFT CONTRAIL-FORMATION CURVES

Section I

THEORETICAL DERIVATION

1.1. Introduction.

The theoretical basis of the original AWS Manual (AWSM 105-100, 1 April 1952) on contrail forecasting was published in January 1953 [2]. This paper derived curves showing the amount of mixing between the environment and exhaust gas which would result in a wake: (1) saturated with respect to water, (2) saturated with respect to ice, and (3) saturated with respect to ice plus a sufficient ice-crystal content to be detected visually. Since the concentration of ice crystals required for a visible contrail is unknown, two suggested estimates were used: $0.004 gm/m^3$ and $0.01 gm/m^3$. It was emphasized that when actual measurements become available, it might be necessary to construct new curves. Such measurements probably will not be made for several years.

The original tables and graphs were worked out in terms of mixing ratio (gm/kg), which means that they cannot readily be adjusted for new concentration values. Therefore, the original calculations have been reworked in terms of vapor density (gm/m^3). As shown later, it is now a simple matter to derive formation curves based on any ice-crystal concentration desired. Also, the new tables can readily be extended to any altitude and adjusted for any fuel. The Tables (see Appendix) and Figures (Figures 1 and 2) for the region 1000 to 40 mb are included in this report for use in further investigations.

Among the products of combustion of hydrocarbon fuels (gasoline, kerosene, fuel oil, etc.) are heat and water vapor. The heat released acts to reduce the relative humidity in the wake of the aircraft, the moisture released acts to increase it. The resulting relative humidity in the wake (RH_e) is dependent on the amount of heat (ΔH) and water vapor (ΔW) contained in the exhaust, the initial temperature (T_E), pressure (P), and relative humidity (RH_E) of the environment, and the ratio (N) of entrained environment to exhaust gas in the wake. Knowing ΔH and ΔW, it is possible to obtain curves of N as functions of P, T_E, and RH_E which will result in specific values of

relative humidity in the wake. (Hereinafter, the subscript "e" will refer to the wake and "E" to the environment.)

It is generally accepted that at temperatures below freezing and in the absence of ice crystals the relative humidity must reach saturation with respect to water before any condensation can occur. At the low temperatures (-40°C and colder) necessary for exhaust-trail formation the resulting droplets immediately freeze. Since the wake is highly supersaturated with respect to ice, the excess water vapor sublimes onto the ice particles, which continue to grow until the relative humidity in the wake falls to ice saturation. If the resulting concentration of ice crystals is sufficient, the trail will be visible. The minimum concentration necessary to produce a visible trail is not known, but estimates have ranged as low as 0.004 to 0.01 gm/m^3 [3]. Others have estimated much higher values. In the previous paper [2] it was shown that any wake which reaches a relative humidity of 100% with respect to water contains sufficient excess moisture after formation of ice particles to produce an ice crystal concentration in excess of $0.01gm/m^3$. In that paper, therefore, curves of N vs P, T_E, and RH_E were constructed for wake relative humidities of water saturation, ice saturation, and ice saturation plus an ice-crystal content of $0.01gm/m^3$. As shown below, it is a relatively simple matter to insert other concentration values as more information is gained on the actual ice-crystal content of contrails.

1.2. Method.

For every gram of fuel burned there are produced approximately 12 grams of exhaust gases containing 1.4 grams of water vapor and 10,000 calories of heat. Each gram of the exhaust gas mixes with N grams of the surrounding air, with N increasing with time from zero to infinity. The increase in temperature of the wake over the initial temperature of the environment (ΔT) is equal to $10,000/(12N \times 0.24)$, where 0.24 is the specific heat of the air. The increase in water vapor density of the wake ($\Delta\rho_{we}$) is $1.4 \times \rho_e/12N$, where ρ_e is the total density of the wake. Since the earlier study had shown that no trails could form until the value of N exceeded 60 parts of air to one of exhaust gas, all wake densities were calculated on the basis of pure air. Combining the two equations to eliminate N, $\Delta\rho_{we} = .0336 \times \Delta T \times \rho_e$, where ρ_e is in units of kg/m^3.

The water-vapor density initially present in an environment at

relative humidity values of 0, 60, 90, and 100 percent, and at 5°C temperature intervals from -20 to -70°C, are shown in Table Ia. These values were calculated from Table 108 Smithsonian Meteorological Tables, 6th rev. ed. Since the Table extended only to -50°C, graphical extrapolation was used to obtain the remaining values. The resulting inaccuracies apparently had a negligible effect on the final curves.

Table Ib shows the vapor density in a wake saturated with respect to water as a function of T_E and ΔT, using ΔT-values of 35, 20, 10, 5, 2, and 1°C. The saturation density values were obtained from Table 108 of the Smithsonian Tables using wake temperatures (T_e) which were obtained by adding T_E plus ΔT. Similarly, Table Ic shows the vapor density in a wake saturated with respect to ice, and are based on Table 109 of the Smithsonian Tables.

Part of the water vapor necessary to form a contrail is contained in the environment, as shown in Table Ia. The amount of additional water vapor necessary to form a saturated wake, which must come from the burning fuel, can be obtained by subtracting the values in Table Ia from those in Ib and Ic. The results are shown in Tables IIa and IIb. Table IIc shows the additional water vapor required to form a wake saturated with respect to ice plus an ice crystal content of .01 gm/m^3. It was obtained merely by adding .01 to all values of Table IIb. Any other desired ice-crystal concentration can be added to Table IIb in the same manner.

In order to obtain the density of water vapor in the wake provided by the fuel ($\Delta\rho_{we}$), it is first necessary to obtain the density of the wake (ρ_e). These values, shows in Table III as functions of P, T_E, and ΔT, were obtained from Table 70 of the Smithsonian Tables. Table IV — the density of water vapor added to the wake by the burning fuel — was then calculated directly from Table III using the aforementioned equation $\Delta\rho_{we} = .0336 \, \Delta T \, \rho_e$.

Thus, Table IIa shows the additional density of water vapor required to bring the wake to saturation with respect to water and Table IV shows the water vapor available from the fuel. Both sets of curves can be plotted on a single graph with x- and y- axes of T_E and ρ, respectively, for specified values of P, RH_E, and ΔT. The intersections give the critical temperatures for a wake saturated with respect to water as a function of P, RH_E, and ΔT (Table Va). Replacing the curves from Table IIa with those from Tables IIb and IIc gives the

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critical temperatures for wakes saturated with respect to ice (Table Vb) and wakes saturated with respect to ice plus an ice-crystal concentration of .01gm/m^3 (Table Vc). The values shown in Tables Va and Vc are plotted as the solid and dashed curves respectively in Figures 1a to 1p; those from Table Vb are plotted in Figures 2a to 2j.

Figures 1 and 2 show the values of N for which a trail will meet the specified humidity conditions as a function of T_E for particular values of P and RH_E. All curves are double-valued with respect to temperature except the cases where the environment is saturated and no ice-crystal concentration is considered [100%-curves Figure 1 (solid lines) and Figure 2]. Thus, there are two values of N which provide exactly the specified humidity for each temperature line which intersects the curves. At smaller and larger values of N the humidity would be less, ac in-between values it would be higher.

Figure 1 can be used to give the persistence of the trail in terms of N-values, assuming saturation with respect to water must be reached before the trail can form and that the trail becomes invisible if the ice-crystal concentration falls below .01gm/m^3. Knowing the meteorological parameters of the environment, the proper curve is selected on the basis of P and RH_E. Then using the value of T_E, the isotherm is followed upward until the solid curve is intersected and the value of the ordinate (N_1) read off. The isotherm is continued upward until it intersects the upper part of the dashed curve which has doubled back, and this ordinate (N_2) obtained. (Note: The doubling back of the 90 and 100% dashed curves occurs at N values greater than 3500.) The points N_1 and N_2 are the amount of mixing required for formation and for dissipation of the trail. Later, when actual ice-crystal concentrations in contrails are measured, it may be necessary to recalculate the dashed curves of Figure 1 which will result in new values of N_2.

The values of N_1 and N_2 were plotted as functions of temperature and pressure for each of the four relative-humidity curves (Figures 3 and 4, respectively). Thus if P, T_E, and RH_E are known, the values of N at which the trail starts and stops can be readily determined. The curves of the maximum value of N at which the wake can become saturated, shown in Figure 3 (and reproduced as dashed curves in Figure 4), were obtained by using the isotherm tangent to the double-valued solid curves in Figure 1. Since the 100% curve was not double-valued, the maximum value of N selected was the maximum value tested, i.e., 3500.
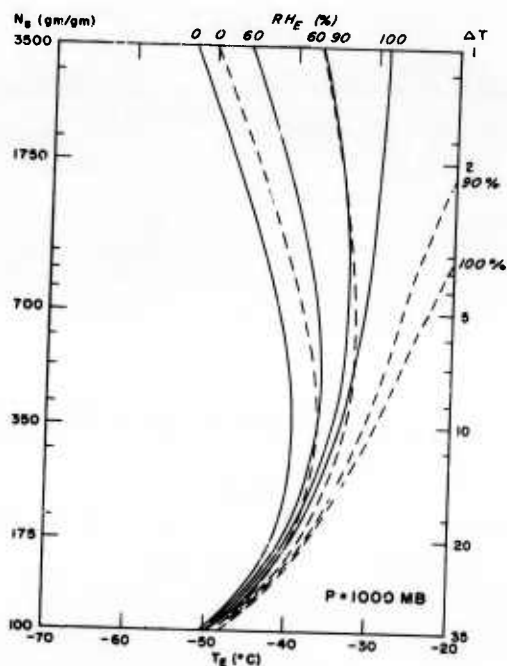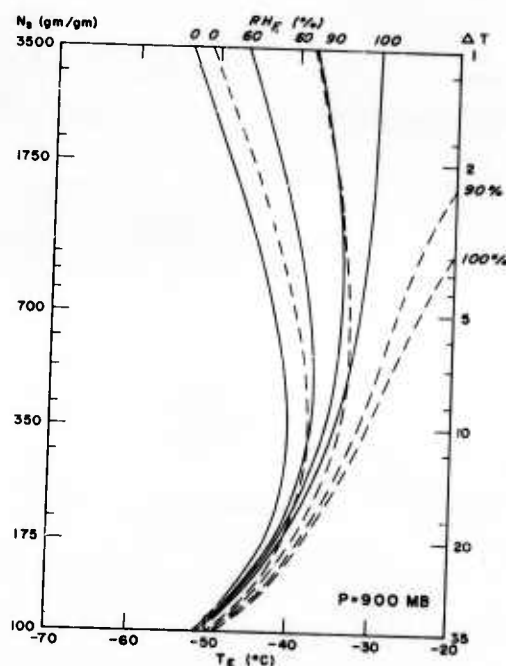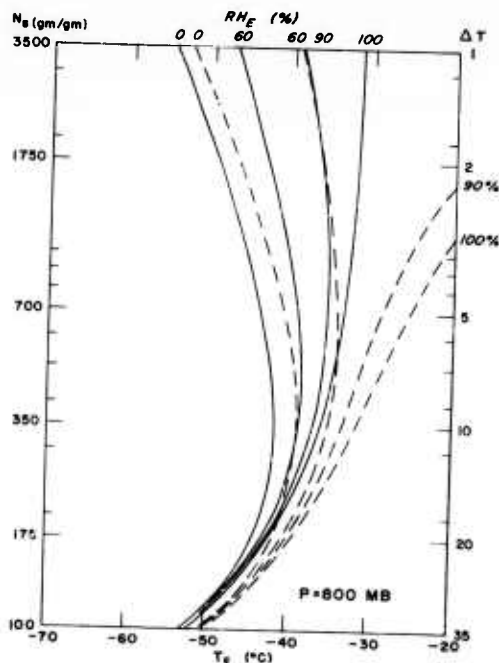
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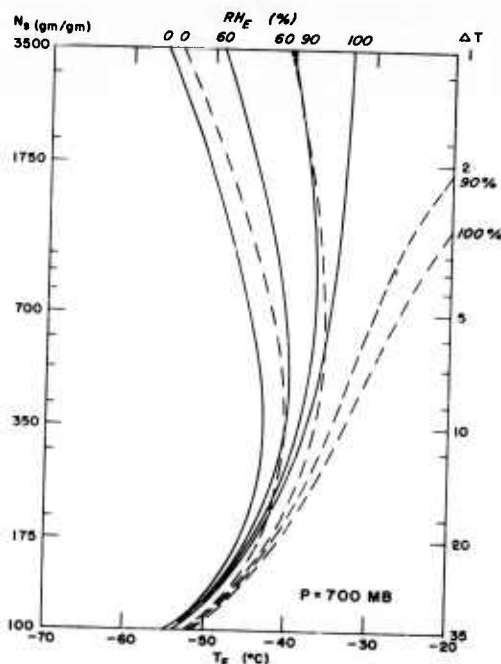
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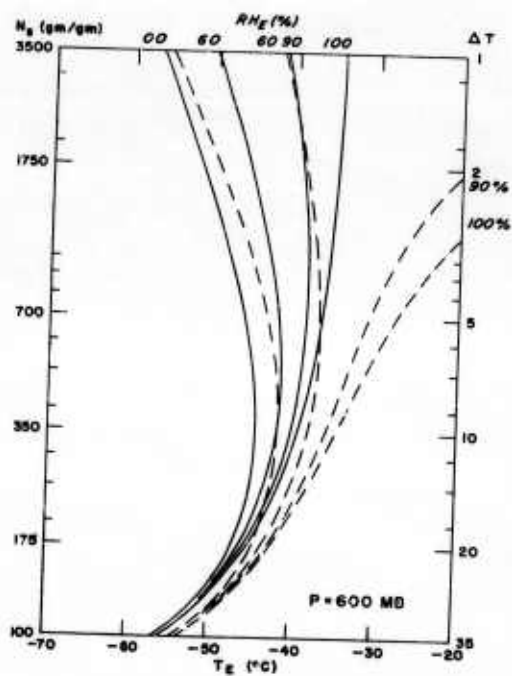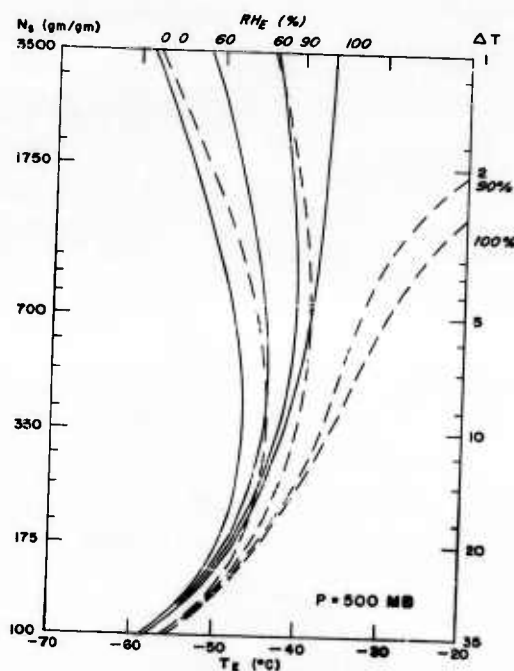
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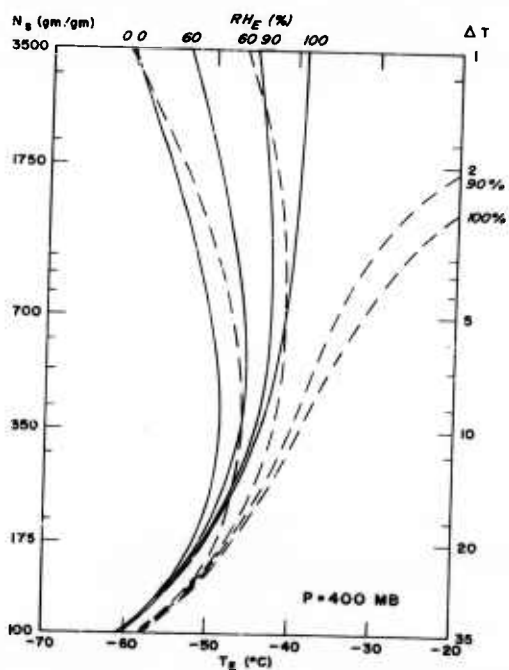
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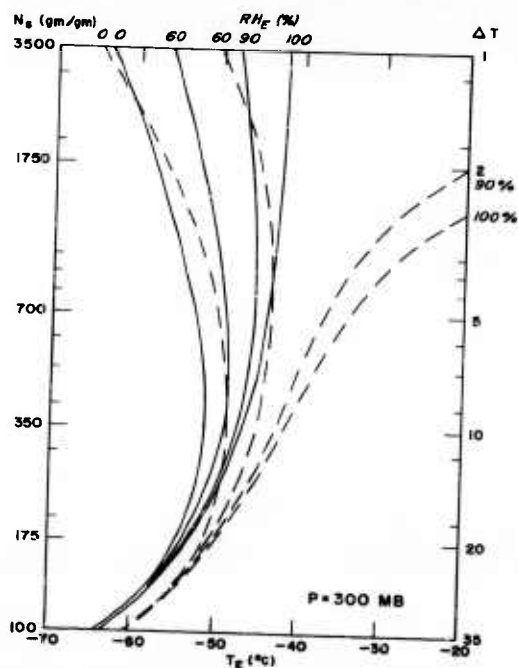
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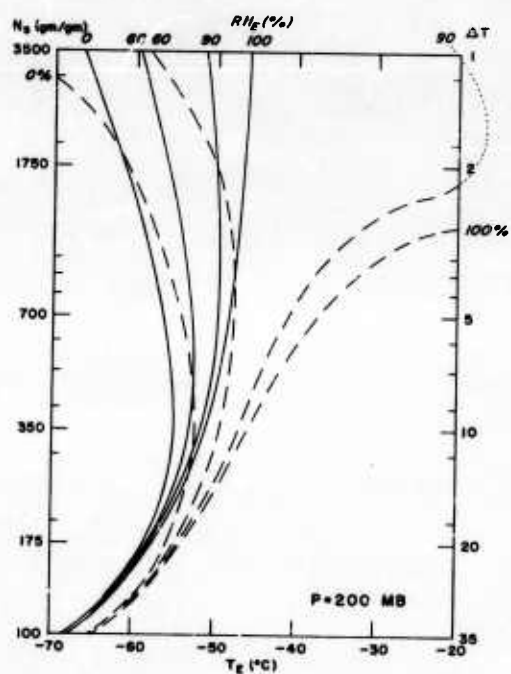
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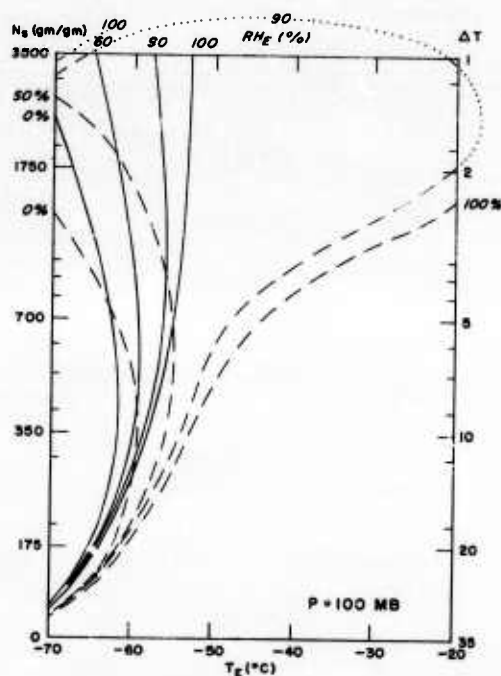
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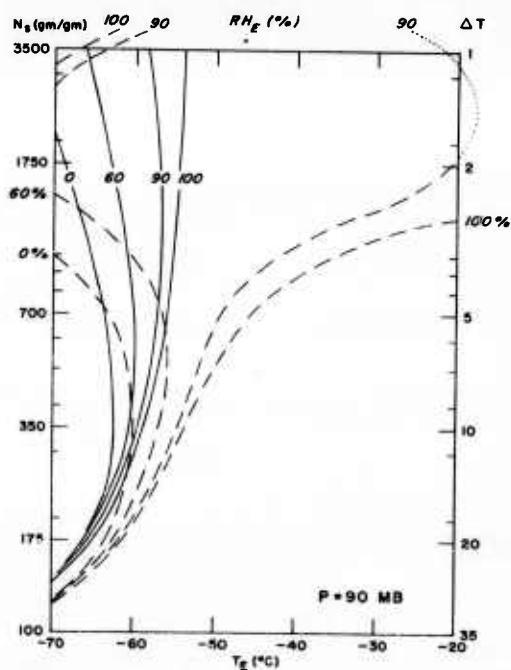
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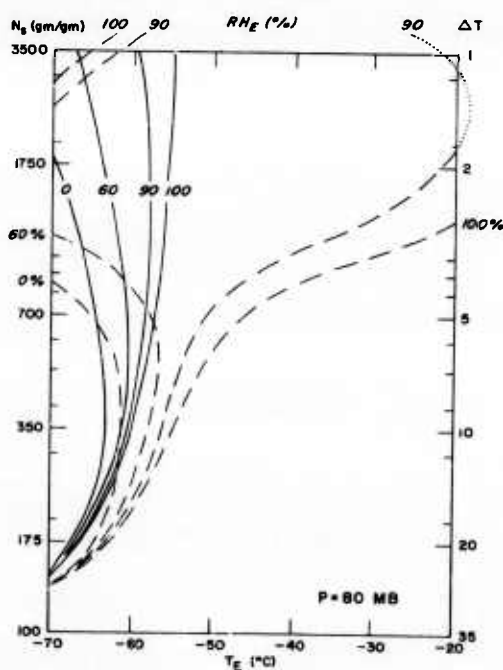
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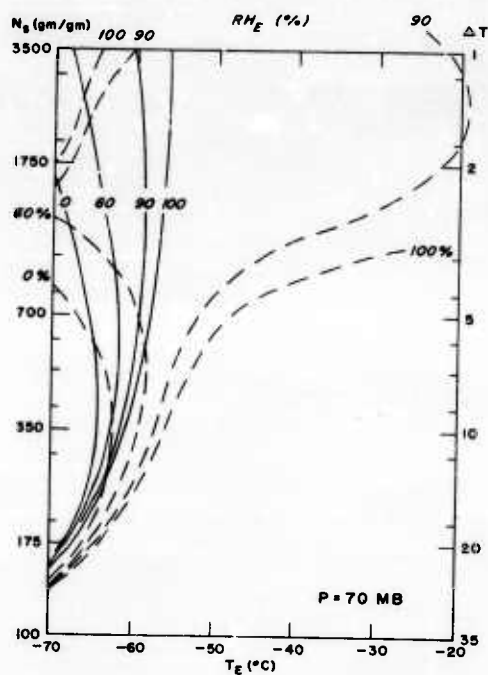
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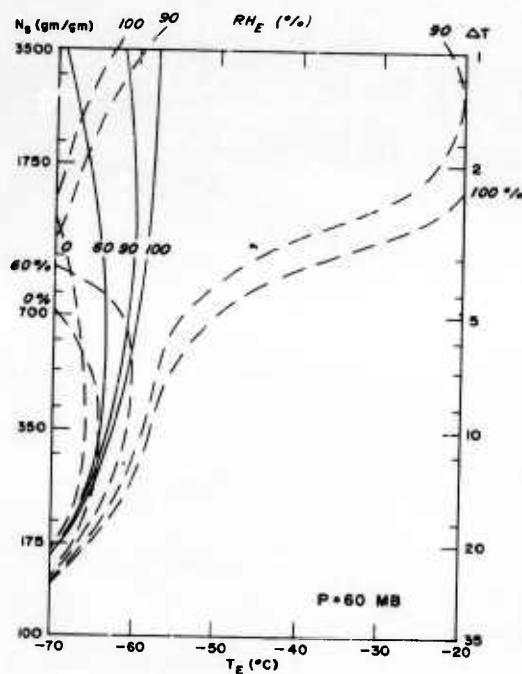
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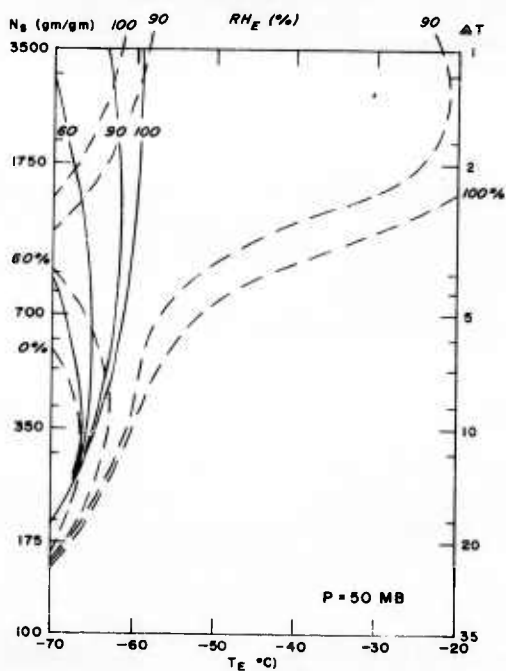
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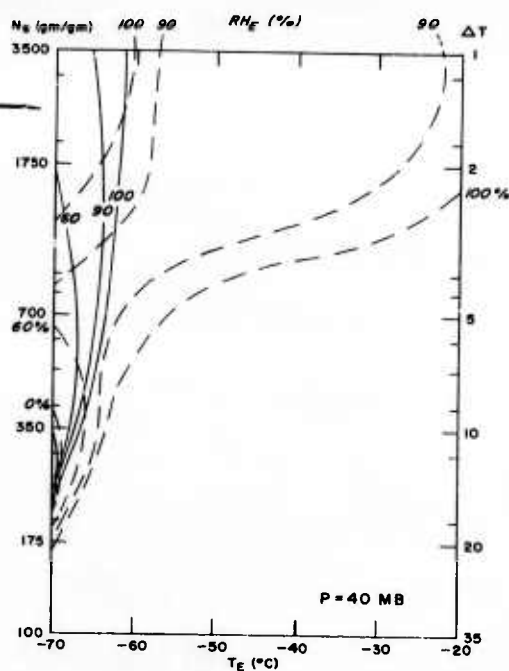
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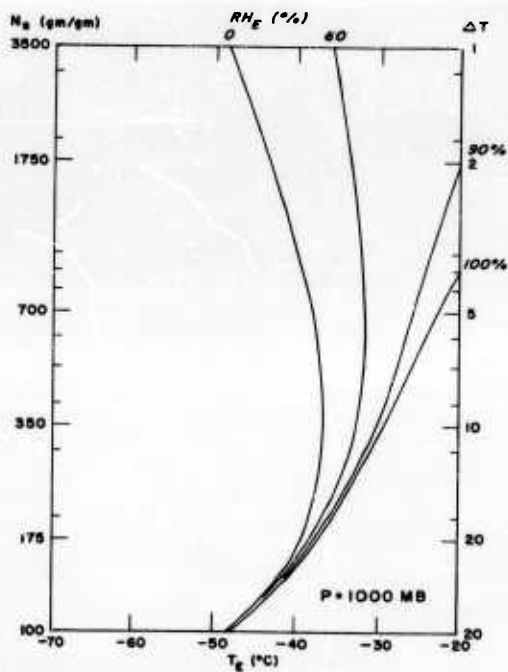
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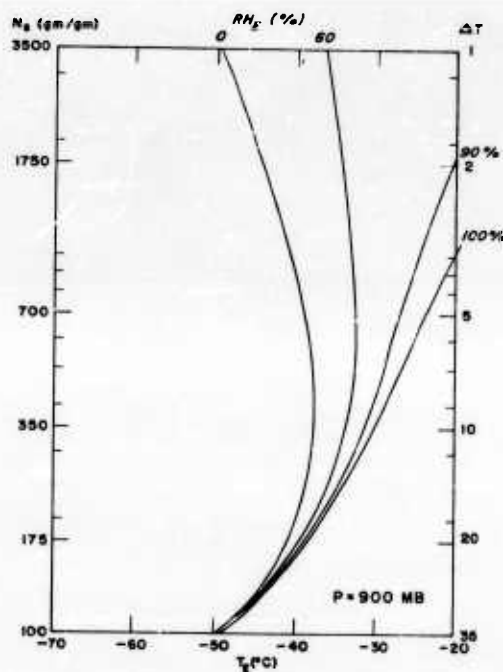
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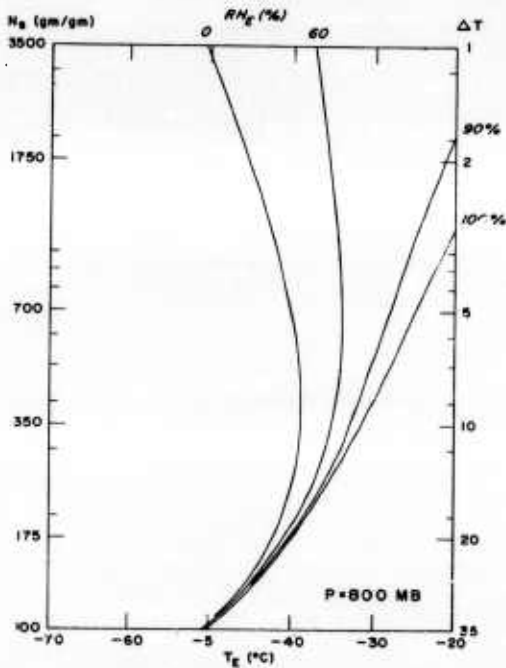
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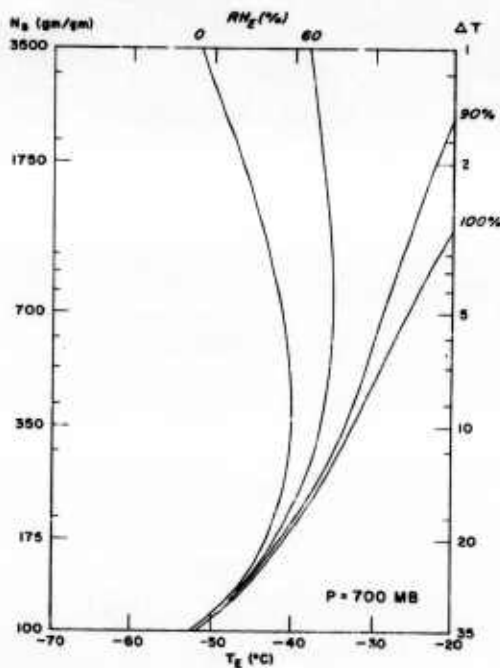
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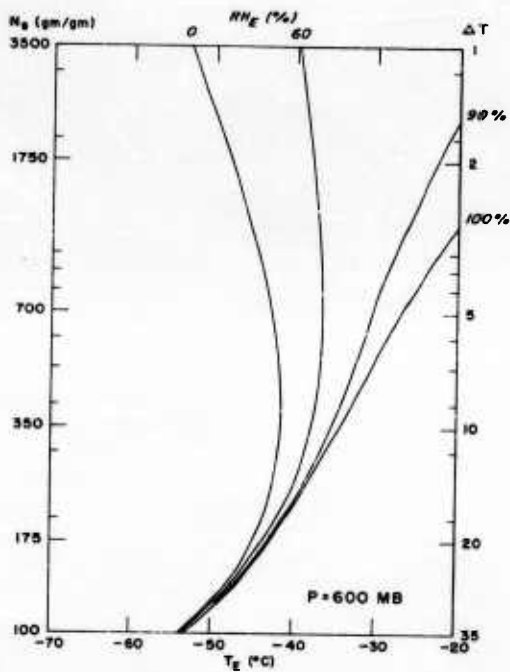
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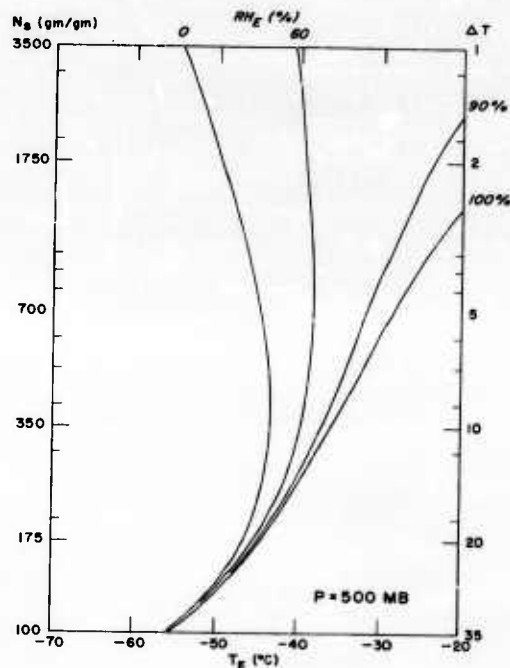
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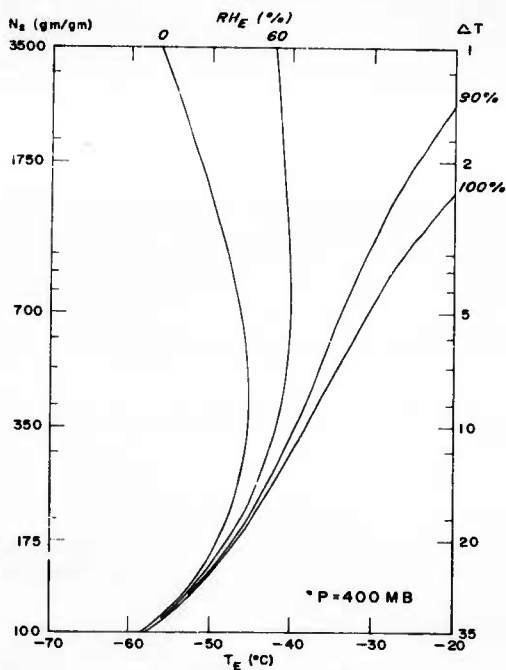
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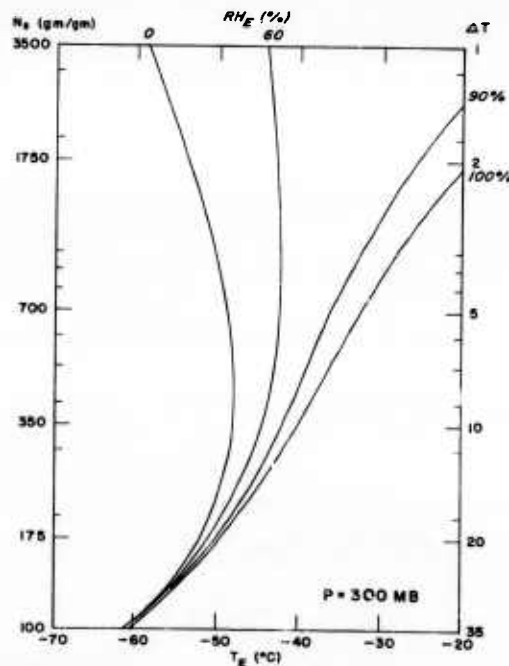
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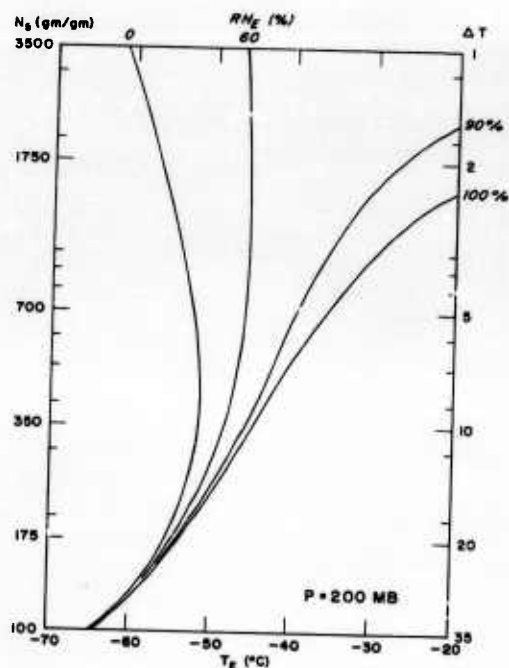
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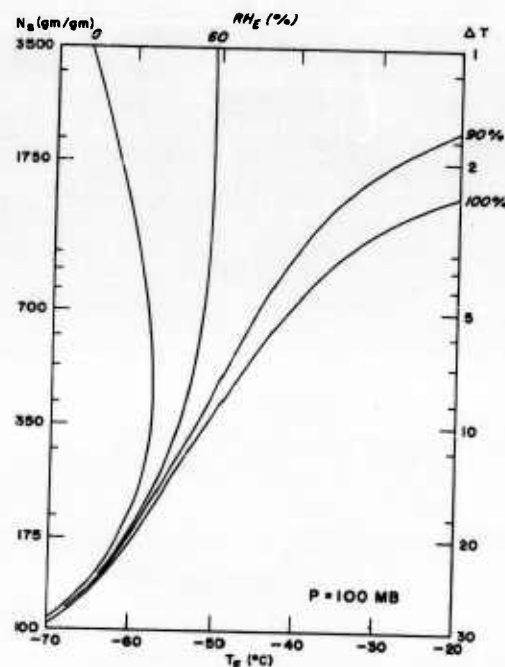
Figure 2j.

At this point the curve was very nearly asymptotic to the isotherms. In all cases the asymptotic value of N on the solid curve lies to the left of the corresponding dashed curve, indicating that a wake saturated with respect to water will contain more than enough moisture to provide a wake saturated with respect to ice plus an ice-crystal content of $0.01gm/m^3$.

The isotherm tangent to a solid curve in Figure 1 indicates the maximum temperature which can exist for the given value of P and RH_E and still result in a saturated wake. The curves of these maximum temperatures are the formation curves in Figure 5 (Figure 1 of AWSM 105-100 Rev). They can also be considered as curves of the minimum relative humidity required for contrail formation as a function of pressure and temperature. This is the more useful form since T_E generally is known more accurately than RH_E. These curves should be identical to those in Figure 4 of the original paper [2] and are very nearly so. To use the curves it is necessary to use known or forecast values of P and T_E. If the point falls to the right of the 100% curve,
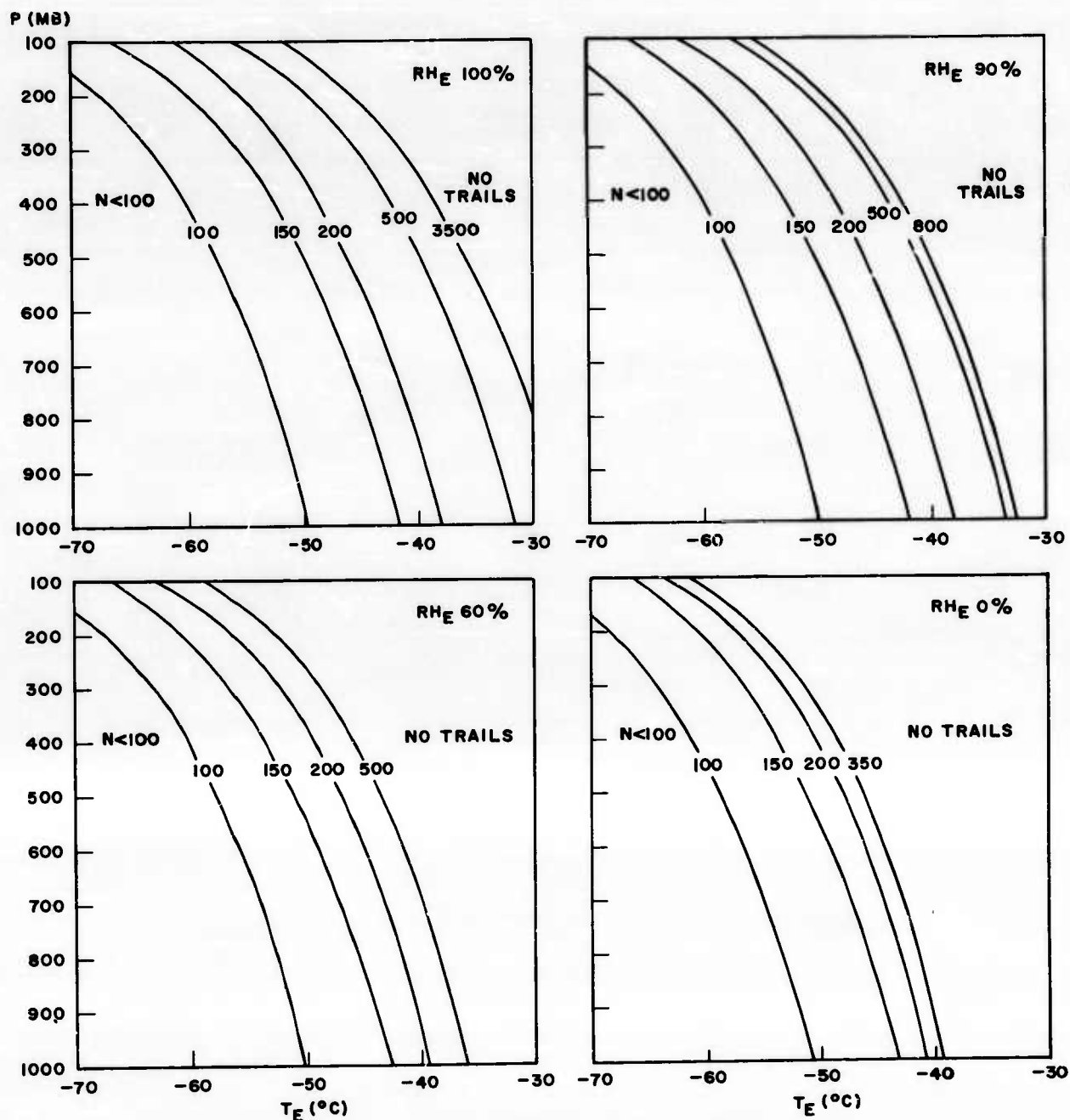
Figure 3. Value of N at time trail becomes visible, as a function of the pressure, temperature, and relative humidity of the environment.
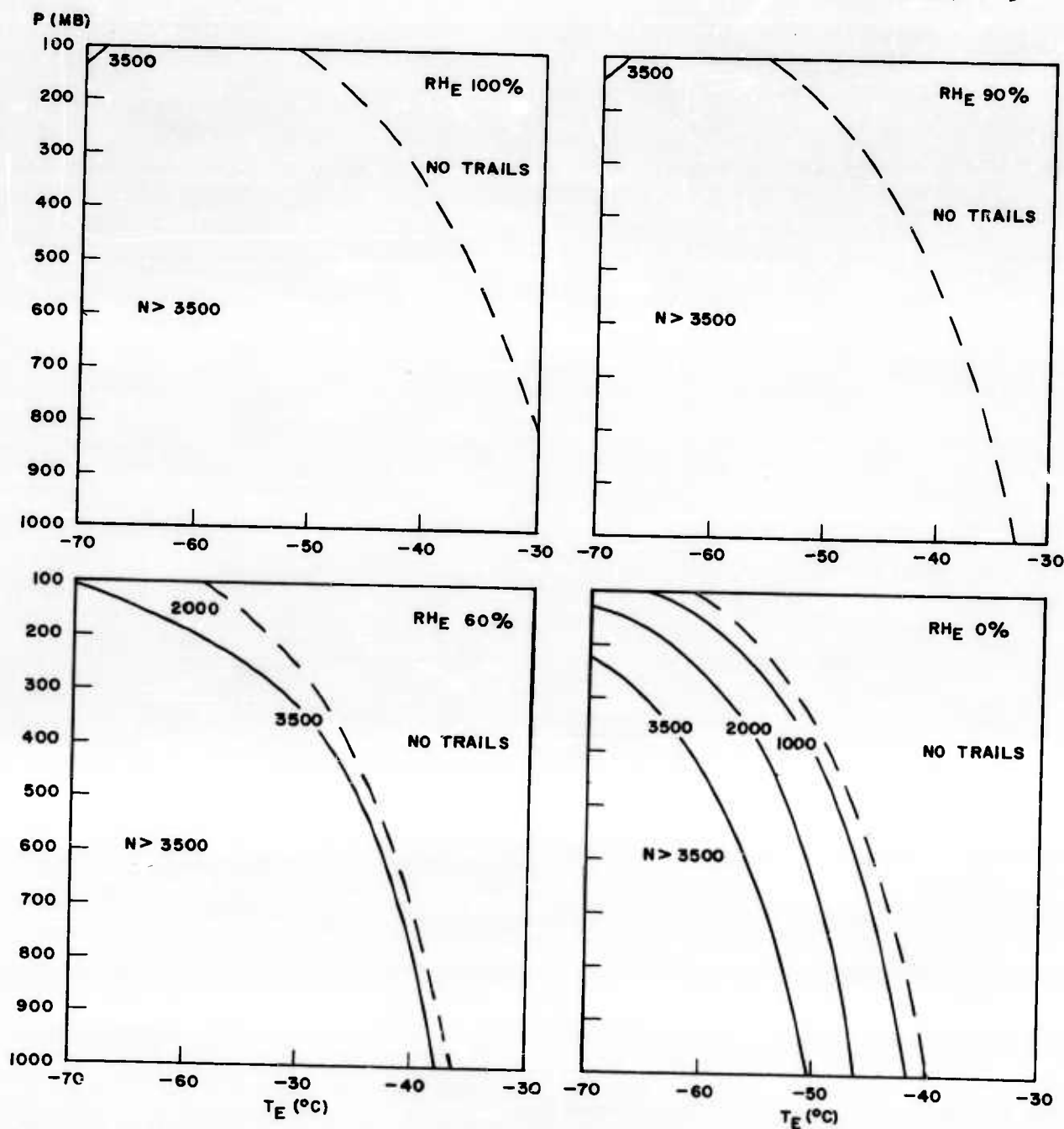
Figure 4. Value of N at time ice-crystal content of trail falls below .01gm/m^3, as a function of the pressure, temperature, and relative humidity of the environment.
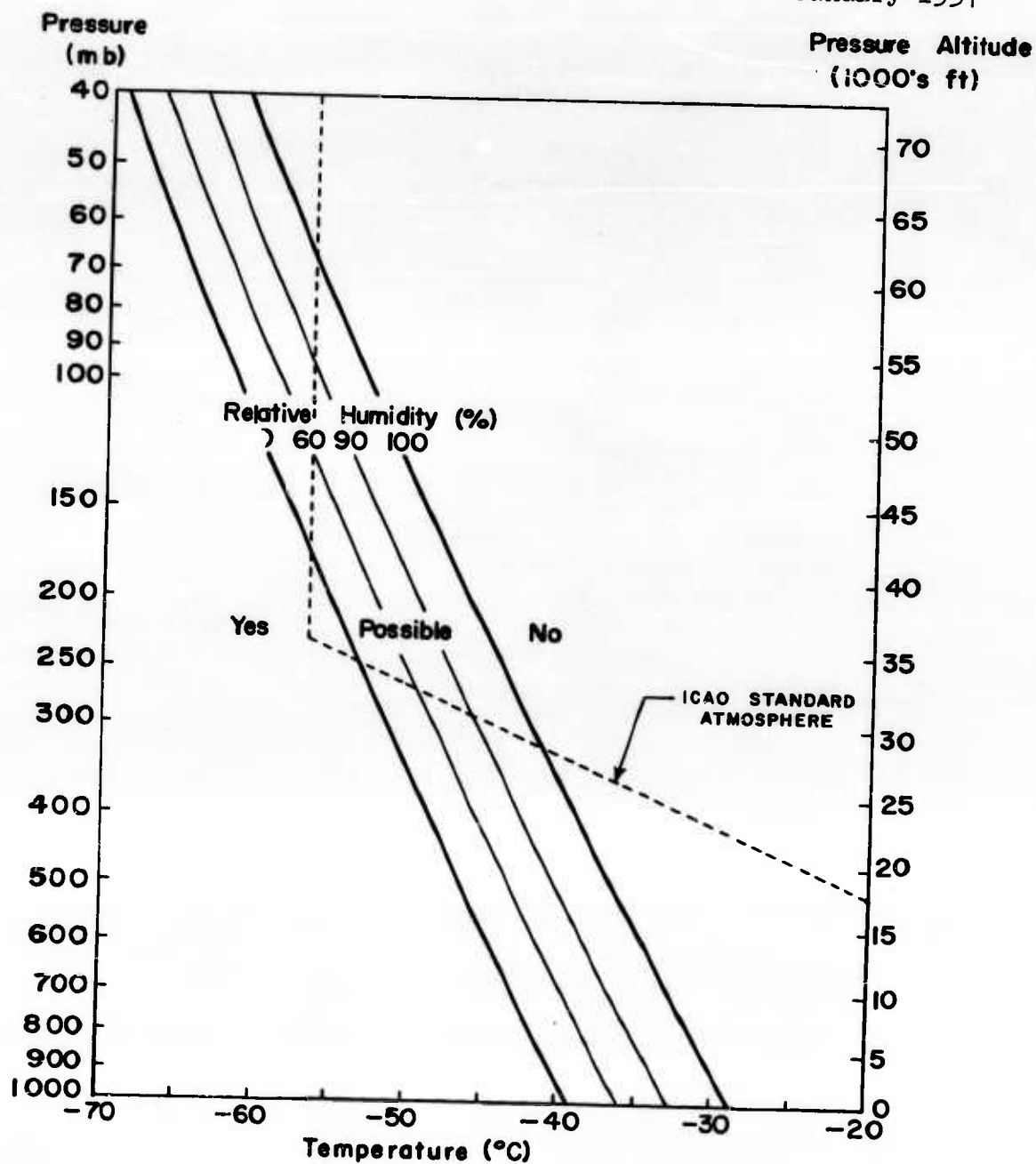
Figure 5. A graph of the relative humidity required for jet-aircraft contrail formation as a function of pressure and temperature of the environment. (Same as Figure 1 of AWS Manual 105-100 Rev.)

trails should not form even if the environment is saturated with respect to water. If the point falls to the left of the 0% line, trails should form even if the environment contains no water vapor at all. If the point falls between the two boundaries, the value of RH_E must exceed that indicated by the graph in order for trails to form.

1.3. Summary.

The theoretical curves presented in this report (Figure 1) indicate at what values of N (the ratio of entrained environment to exhaust gas in the wake) visible contrails start and dissipate. It is assumed that visible trails start when the wake becomes saturated with respect to water, and dissipate when the ice-crystal concentration falls below $0.01 gm/m^3$. The latter assumption is open to question until actual measurements are made. When data do become available, however, it will be a simple matter to adjust Table VIIb and combine it graphically with Table IV to obtain new curves to replace the dashed curves of Figure 1.

The use of Figure 1 gives the persistence of visible trails in terms of N-values. As stated in the earlier paper [2]: "The relationship of N to distance behind the airplane is affected by the type of aircraft, its control settings, the stability and density of the surrounding atmosphere, and the radial distance outward from the central axis of the trail. It would be possible to carry out individual studies for various types of aircraft under various conditions of atmospheric stability in order to obtain the exact relation between N and distance behind the airplane. This would enable the translation of the formation and dissipation points of the trail from values of N into terms of distance, thus giving the length of the trail."

Curves for fuels which, upon combustion, liberate quantities of heat and moisture different from those used in this report can be constructed merely by recalculating Table IV. Also, by extending Table IV to lower pressures, contrail curves can be obtained for any altitude. These studies have now been carried out to 40 mb. Because of the uncertainty in the amount of water vapor required to saturate air at very low temperatures, the curves can be carried no higher at this time.

Section II

EMPIRICAL DERIVATION

2.1. Introduction.

Chapter II of AWSM 105-100 Rev. and Section I of this Report discuss theoretically-derived curves (Figures 1-5) which show the pressure-temperature relative-humidity relationship necessary for contrail formation by the exhaust from jet aircraft. By forecasting or assuming temperature and relative-humidity values for the pressure-level of interest, it is possible to issue a Yes/No type of contrail determination or forecast. Unfortunately, in addition to the usual inaccuracies inherent in all space and time forecasts, there are special difficulties in forecasting the temperature and relative humidity at the altitudes and temperatures where contrails can occur.

Due to instrumental difficulties, relative humidities are not ordinarily measured at temperatures below -40°C. Figure 5 shows that nearly the entire theoretical region of contrail formation lies at temperatures below -40°C. In contrail determination and forecasting, therefore, it is necessary to rely on some assumed value of relative humidity that has proved useful over a period of time. AWSM 105-100 (Rev.) recommends using a relative humidity of 70% near the tropopause and in high-cloud layers, and 40% at all other times.

Temperature data as provided by the radiosonde also are not completely representative. To begin with, the temperature element is subject to a standard error of ½° — 1°C. Another small error is introduced by the limitation to the number of significant levels that can be worked up and transmitted. Together, these two inaccuracies give a standard error of close to 1° — 1½°C (cf. AWS TR 105-133). More important, however, are the very large horizontal temperature gradients that occasionally exist aloft. Measurements [1] have shown gradients up to 11°C/60 nautical miles with a possible gradient of 13°C/30 nautical miles. This temperature uncertainty must be kept in mind when using Figure 5 (cf. AWSM 105-100 (Rev.) Chapter II). For all practical purposes it amounts to a narrowing of the Yes- and No-areas of the graph, and a widening of the Possible-area. The spacing of the relative-humidity curves on Figure 5 shows that the left side of the

Possible-area is extremely sensitive to temperature errors while the right side is relatively insensitive. For example, a temperature error of 1°C is equivalent to a relative-humidity error of 22% on the left edge of the area, only 1.5% on the right edge — a sensitivity ratio of about 15 to 1. Thus, it is the left side of the graph which is primarily affected by the temperature uncertainty.

To by-pass the presently unavoidable temperature and relative-humidity errors, it was decided to obtain sufficient data to make an empirical study of contrail frequency as a function of pressure and temperature alone. In this way both the temperature uncertainty and the actual mean relative humidity at each pressure-temperature point are absorbed into the frequency curves. This method does not allow a Yes-No forecast; it does, however, permit a statement as to the relative frequency (i.e., empirical probability) of contrail formation for any given value of pressure and temperature.

2.2. Procedure.

Project Cloud Trail was established within the Air Defense Command, in conjunction with Air Weather Service, to collect high-level weather information from jet aircraft. The aircraft were to accumulate sufficient data to serve as a basis for improved methods of forecasting contrails, cirrus clouds, haze, and turbulence. Only the contrail portion of the Project is considered here. The observational phase of the Project ran from 1 December 1954 to 15 December 1955. During this period, 36 fighter-interceptor squadrons based in the United States collected data over 23 upper-air sounding stations. The procedure employed was as follows:

a. Each day from approximately one hour before to two hours after 1530 GCT, two aircraft were vectored to a point 25,000 feet above an upper-air sounding station. The aircraft then climbed to the maximum altitude obtainable, maintaining position within 30 miles of the station.

b. The wingman observed whether or not the lead aircraft produced exhaust trails and whether they were continuous or intermittent, distinct or faint, including bases and tops of layers in which the trails formed.

c. Other requested data were gathered.

As the data cards were received at Headquarters Air Weather Service, the associated soundings were plotted from the Daily Upper-Air

Bulletins. The contrail levels were then entered on each sounding. For six selected pressure levels — 350, 300, 250, 200, 175, and 150 mb — the occurrence and non-occurrence of contrails and the associated temperatures were picked off. A tabulation was made of the number of contrail, no-contrail, and total cases for each degree of temperature at each pressure level, and the percentage of cases having trails determined. A plot of contrail frequency against temperature was made for each pressure level and smooth curves drawn. The resulting contrail frequency-function curves obtained by lumping together the data from all the stations for the year are shown as solid lines in Figure 6 — (the purpose of the dashed lines is explained below).
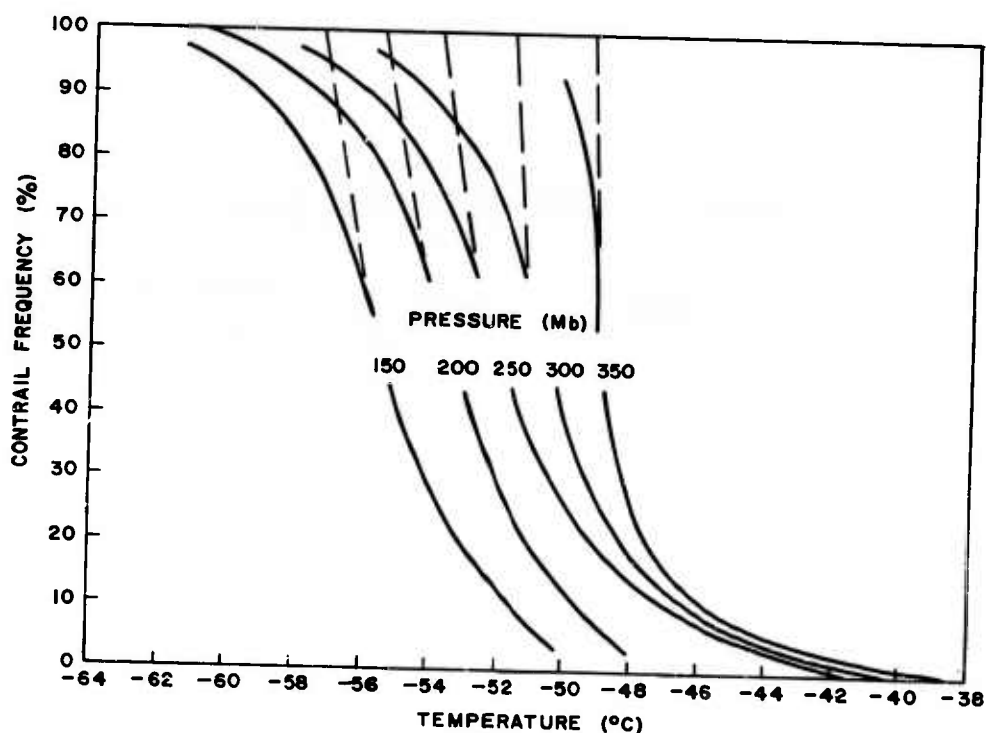
Figure 6. Contrail frequency as a function of temperature and pressure, United States, December 1954 — November 1955.

The temperature values for several selected contrail frequencies — 5, 10, 25, 50, 75, 90, and 95% — were picked off from each graph. The pressure-temperature coordinates of these selected frequencies were plotted and smooth curves drawn of contrail probability as a function of temperature and pressure (solid lines, Figure 7). For purposes of

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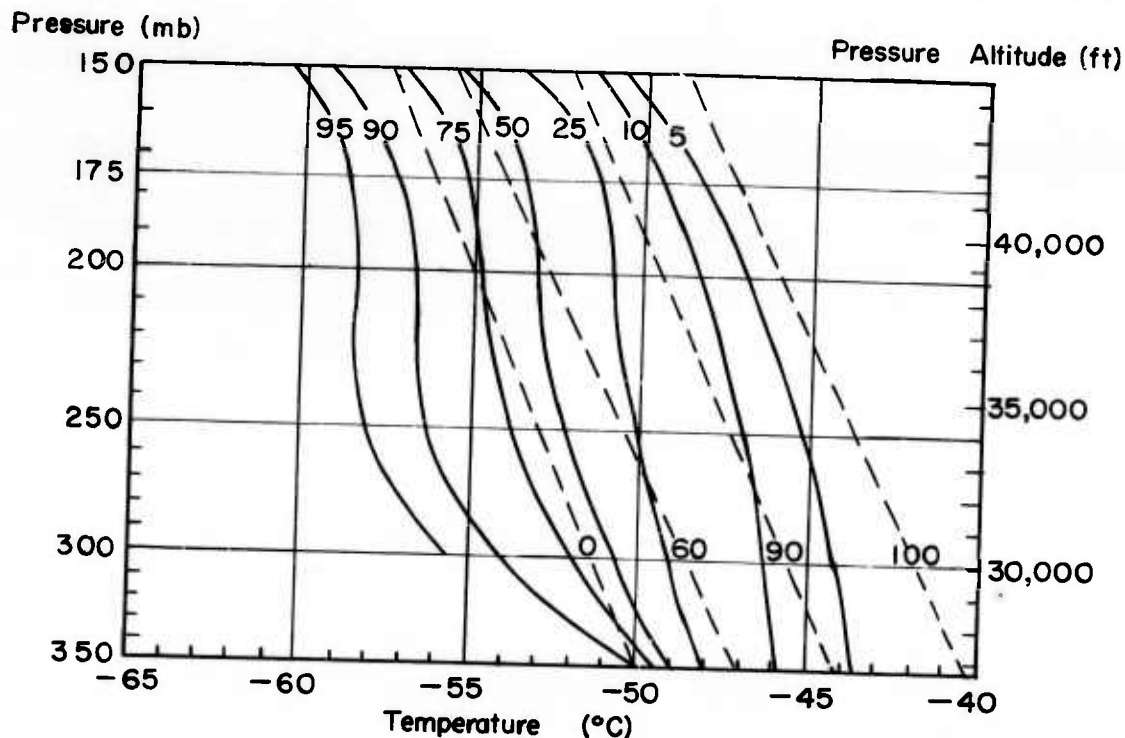
Figure 7. Probability of jet-aircraft contrail formation as a function of pressure and temperature. Solid lines are empirically-derived curves of contrail probability in percent. Dashed lines are theoretically-derived curves of minimum relative-humidity (%) required for contrail formation. (Same as Figure 3 of AWS Manual 105-100 Rev.)

comparison the four theoretically-derived contrail-formation curves are entered in Figures 6 and 7 as dashed lines. Certain discrepancies between the empirical and theoretical curves are discussed in following sub-sections.

2.3. Comparison of the Theoretical and Empirical Curves.

Assuming the theoretically-derived curves are exact, perfect data would result in the 0% probability curve coinciding with the 100% humidity line, and the 100% probability curve with the 0% humidity line. Assuming further an equal chance for all relative humidity values at every pressure-temperature point, the 90% and 60% humidity lines should also coincide with the 10% and 40% probability curves, respectively. However, one would not expect the distribution of mean relative humidities to be constant with altitude; hence, it is only the bounding curves that can be tested. Figure 7 shows that although the right side

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of the empirical and theoretical curves are in good agreement, there is a discrepancy of 5 or 6°C on the left side. To thoroughly understand the reason for this discrepancy, it is useful to go back to the contrail-frequency-function curves for the individual levels (Figure 6).

A study of Figure 1 shows that near the 0% relative-humidity line a small change in temperature is equivalent to a large change in relative humidity. The opposite is true near the 100% line. Assuming an equal chance for all relative-humidity values at every pressure-temperature point, resulting contrail-frequency-function curves would start out flat, then become progressively steeper toward the upper end (Figure 8). If the relative-humidity values were evenly distributed
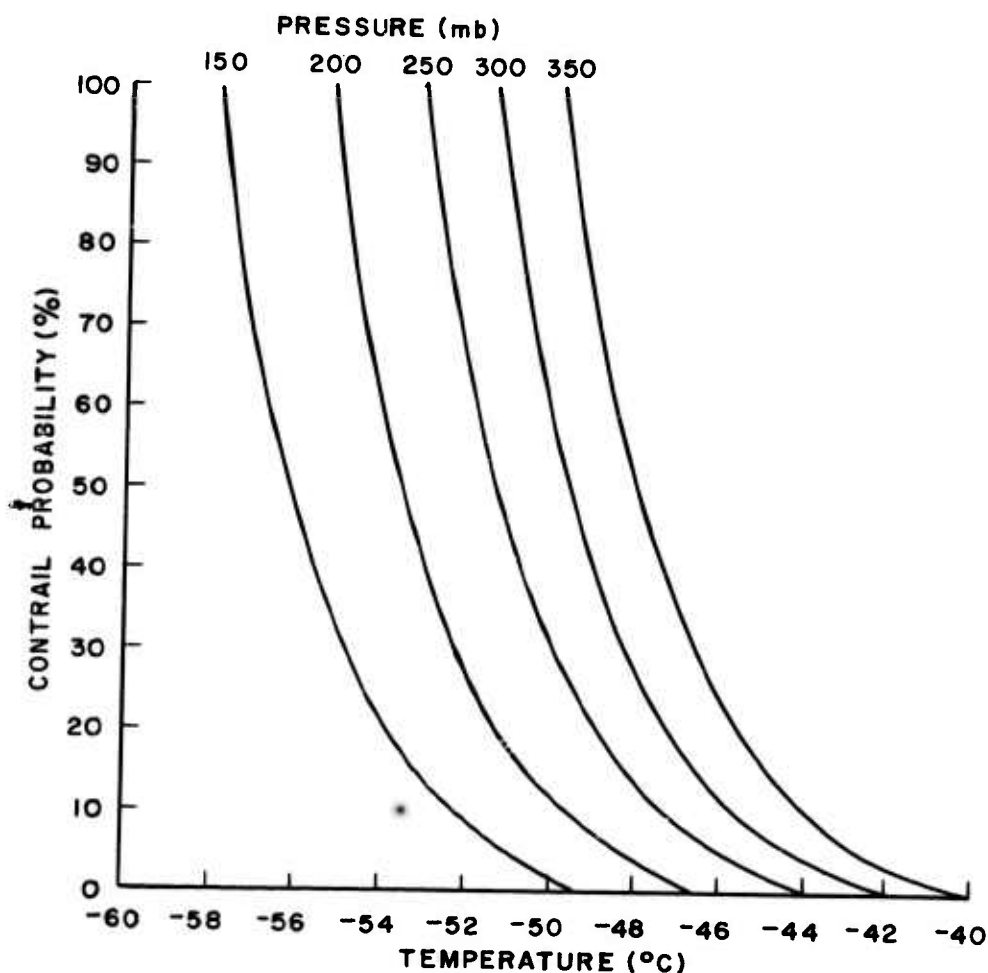
Figure 8. Theoretical contrail-probability-function curves obtained by assuming an equal distribution of all relative-humidity values from 0 to 100% for each pressure point.
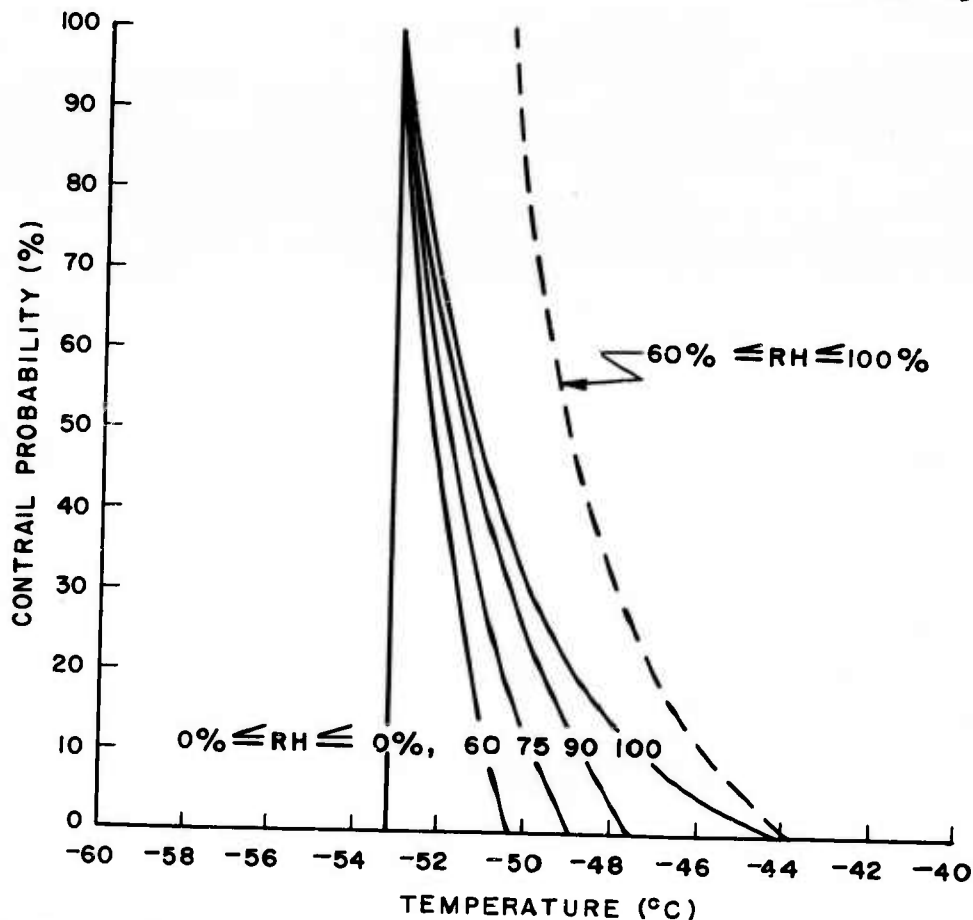
Figure 9.   Theoretical contrail-probability-function curves
for 250 mb obtained by assuming an equal distribution of
all relative-humidity values between 0% and each of five
arbitrary maxima (solid curves), and between 100% and an
arbitrary minimum (dashed curve).

but had a minimum cutoff above 0% or a maximum cutoff below 100%, the
flattening effect at the lower ends of the curves would be reduced.
This effect is shown for the 250-mb level in Figure 9.   (Note: The
curve $0 \leq RH \leq 100$ is identical with the 250-mb curve of Figure 8.)
Figure 10 shows the effect on contrail probability of a normal distri-
bution of relative humidity about a mean value of 50% with a standard
deviation of 20%.   With this distribution, 68% of the cases fall be-
tween 30 and 70% relative humidity and 95% of the cases between 10 and
90% relative humidity.   It is seen, then, that any reasonable relative-
humidity distribution results in contrail frequency curves which are
more or less flat at the lower end and become progressively steeper at
the upper ends.

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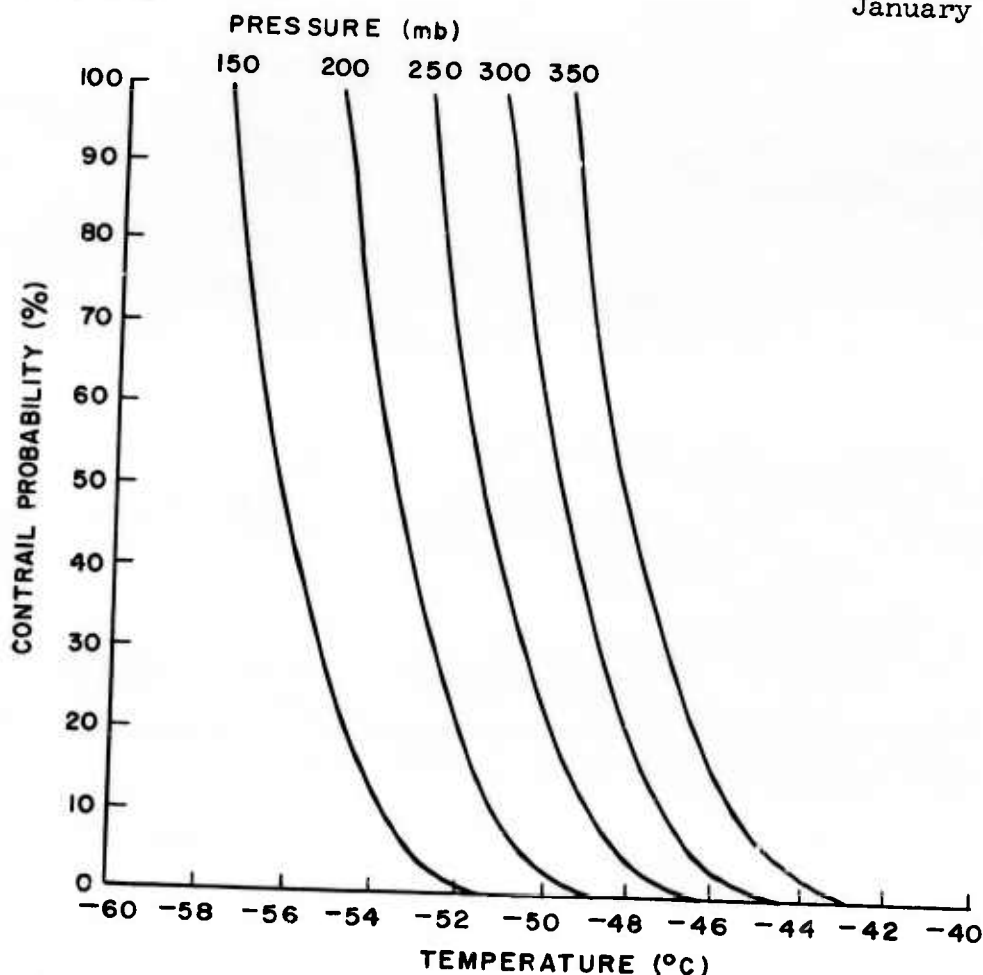
Figure 10. Theoretical contrail-probability-function curves obtained by assuming a normal distribution of relative humidity about a mean of 50% with a σ of 20%.

The contrail-frequency-function curves of Figure 6 show the expected flattening at the lower end. However, the progressive steepening of the curves continues only to frequency values of 60 to 80%; thereafter, the curves turn somewhat to the left. This inflection occurs near the left edge of the Possible-area of Figure 5. Since it cannot be attributed to the relative-humidity distribution, it is necessary to consider the other variable, temperature.

It was noted in sub-section 2.1. above that the temperatures from a radiosonde report contain a standard error of about 1°C; more important are the occasional very large temperature gradients that exist aloft. Because of operational requirements, the aircraft were allowed to take off up to one hour before or two hours after raob release time.

Since it takes the balloon about 30 minutes to get to 30,000 feet, the aircraft might be at this point an hour and a half before or after the balloon. Thus, both a space and time difference may exist. With a fairly strong wind at 30,000 feet, say 60 knots, this is equivalent to a total space displacement of more than 50 nautical miles. Usually, the difference would be much less, but in extreme cases it could be more than twice as great. Hence, the temperature measured by the radiosonde could occasionally be 11°C different from that encountered by the aircraft, and in some cases even more.

Temperature errors tend to be self-compensating in the Possible-area of the contrail-formation graph (Figure 5), with just as many cases reported too cold as too warm. However, this compensation is affected adversely by the non-linearity of the frequency curves and by the 0 and 100% frequency boundary lines. The increasing steepness of the curves results in theoretically derived contrail frequencies slightly greater than the observed (empirical) values. The boundary lines result in too-large values of derived contrail frequency at the lower end, too-small values at the upper end, or a flattening of both ends of the curves on the graph (Figure 7). In the Yes- and No-areas, temperature errors can act in but one direction. Erroneous reports would fall into these regions which properly belong inside the Possible-area. This would result in a flattening of both ends of the frequency curves. However, the lower end is already flat. In addition, as pointed out in sub-section 2.1, the left edge of the contrail-formation graph (Figure 5) (which is equivalent to the upper end of the frequency curves of Figure 7) is about 15 times more sensitive to temperature than the right edge. Hence, the effect of temperature errors would be reflected much more strongly in the upper ends of the frequency curves than in the middle or lower portions.

Apparently, then, the inflection of the upper part of the contrail-frequency curves is due primarily to discrepancies between the temperatures measured by the raob and those encountered by the investigating aircraft. This inflection results in a displacement of the higher contrail-frequency values (above about 60%) toward lower temperatures. Hence, the 75, 90, and 95% contrail-probability curves of Figure 7 are also displaced toward lower temperatures, and cannot be expected to coincide with the theoretical curves.

Extrapolating the frequency-function curves smoothly upward with-

out inflection should give the contrail frequencies that would be obtained with perfect data. These are the dashed curves of Figure 6. The critical temperatures for 100% contrail frequency obtained in this way are all within 1°C of the values shown by the theoretically-derived 0% relative-humidity line.

In using the contrail-probability graph (Figure 7), however, the forecaster must contend with the inherent error of the radiosonde instrument and with the unrepresentativeness caused by the occasional intense horizontal temperature gradients. Consequently, when forecasting contrails, he should use the contrail-probability values determined from the actual frequency (empirical) curves, and not (theoretical) curves which would be true only for perfect data.

2.4. Effect of Season on Contrail Probability.

Contrail probability curves similar to those of Figure 7 were constructed for each season (see AWS TR 105-132). Table VI shows a comparison of the corresponding pressure-temperature values of these curves for the individual seasons and for the year. The differences between the annual and seasonal curves were small. Since the differences that did exist showed no consistent seasonal trends, it is probable that they were caused mainly by the limited sample of data for the individual seasons. It seems that any true seasonal effects are too small to be significant for forecasting purposes.

2.5. Effect of Geographical Location on Contrail Probability.

In order to determine whether the contrail probability curves vary significantly in different regions, separate curves similar to those of Figure 7 were constructed for the northern and southern parts of the United States. The dividing line was 39°N. The number of southern stations involved in the test was relatively small, and the number of contrails at low altitudes in the south was negligible. Table VII shows a comparison of the corresponding pressure-temperature values of the contrail-probability curves for the north and south, based on the entire year's data. The average differences between the two sets of points was 0.7°C, with the southern curve averaging 0.2°C colder.

The differences between the two sets of curves were small at all levels. At 250 and 200 mb the northern and southern curves coincided almost exactly; at the other levels the contrail probability tended to be a little higher in the north at temperatures above -57°C, higher in the south at the lower temperatures. The largest temperature difference

between the two sets of curves was never more than 1.3°C. The average
of the differences between the two sets of points was 0.7°C, with the
northern values averaging 0.2°C warmer.

The differences between the contrail-probability curves for the
north and those for the south, while possibly real, are too small to be
significant for forecasting purposes. Consequently, the curves of
Figure 7 can for the present be considered applicable at all locations.
Further study on climatic effects, based on data taken in Europe and
Japan, is planned for the future.

2.6. Effect of the Tropopause on Contrail Probability.

Various studies have been published comparing the humidity in the
stratosphere with that of the troposphere. Because of the limited
number of measurements actually available near the tropopause levels,
however, no completely reliable conclusions can be drawn. Since the
mean relative humidity affects contrail probability, separate proba-
bility studies were carried out for the troposphere and stratosphere.

In order to isolate the effect of the tropopause, it was necessary
to compare stratospheric and tropospheric frequencies at common
pressure-temperature values. The pressure level containing the best
balance of cases above and below the tropopause was 200 mb. Separate
stratospheric and tropospheric contrail-frequency-function curves were
carried out for this level (Figure 11). It is seen that throughout
the greater portion of the curve, for a given value of pressure and
temperature the frequency of trails is greater in the stratosphere than
in the troposphere.

The theoretically-derived critical relative-humidity values for
contrail formation have been entered on Figure 11 as dashed lines. The
50% contrail-frequency line indicates a median relative humidity of
about 40% in the troposphere, 70% in the stratosphere. It must be
kept in mind that this measurement applies particularly to the 200-mb
level. At this level, most of the stratospheric cases would be in
lower polar-stratospheres; most of the tropospheric cases would be in
upper tropical-tropospheres.

The tendency for increased relative humidities near (just above
to just below) the tropopause is also borne out by Figure 7. In gen-
eral, the probability curves are steeper than the relative-humidity
lines up to about 185 mb, then less steep. This indicates that the
mean relative humidity increases from 350 mb to about 185 mb, then
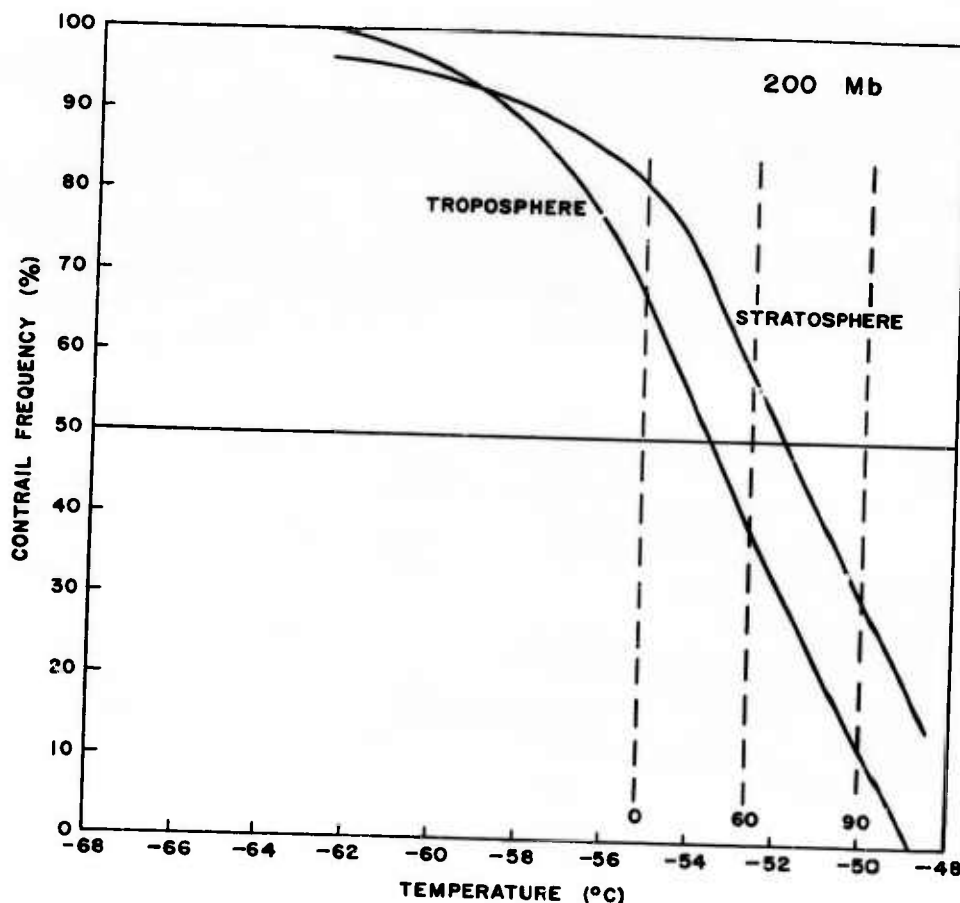
Figure 11. Comparative contrail-frequency-function curves for the troposphere and stratosphere at 200 mb, United States, December 1954 — November 1955. Dashed lines are theoretically-derived values of minimum relative humidity required for contrail formation as a function of the 200-mb temperature.

decreases. Since the mean tropopause height for this study was 210 mb, it appears that the level of maximum mean relative humidity lies about 3000 feet above the mean tropopause. (In all cases of multiple tropopauses only the lowermost was considered in this study.)

2.7. Summary.

Figure 7 presents curves of contrail probability as a function of pressure and temperature. The curves are based on consolidated observations gathered for one year over the entire United States. Inherent data problems encountered by the forecaster in the field are absorbed into the curves. The most important of these problems are the mean

relative humidity at each pressure-temperature point, and the unrepresentativeness of temperatures measured by the radiosonde. The humidity problem is caused by the lack of humidity measurements at the levels where contrails can form. The temperature problem is due partly to the small standard error (about 1°C) in reported temperatures but mainly to the fact that occasionally very strong horizontal temperature gradients exist at the upper levels which can lead to temperature errors of more than 10°C.

To use Figure 7 the forecaster merely makes his best possible temperature forecast for the altitude, time, and place of interest, and enters the graph with this pressure-temperature value to get the probability of contrail formation (see AWSM 105-100 Rev). Unfortunately, contrail-probability curves are available only from 350 to 150 mb. Below 350 mb the temperature was nearly always too warm for trail formation. Above 150 mb there were insufficient observations for the construction of reliable curves. At altitudes outside the 350-150-mb range, the forecaster must use the contrail formation graph (Figure 5).

APPENDIX

TABLE Ia

Density of Water Vapor in Environment (gm/m^3)

Temp. of Environment (T_E, °C)	Relative Humidity of the Environment (%)			
	100%	90%	60%	0%
-70	.006*	.005*	.004*	0
-65	.012*	.011*	.007*	0
-60	.021*	.019*	.013*	0
-55	.037*	.033*	.022*	0
-50	.062	.056	.037	0
-45	.106	.095	.064	0
-40	.176	.158	.106	0
-35	.286	.257	.172	0
-30	.453	.406	.272	0
-25	.705	.634	.423	0
-20	1.074	.966	.644	0

* Indicates doubtful value

TABLE Ib

Density of Water Vapor in Wake Saturated/Water (gm/m^3)

Temp. of Environment (T_E, °C)	Wake Temp. Minus Initial Environment Temp. — (ΔT, °C)					
	35°C	20°C	10°C	5°C	2°C	1°C
-70	.286	.062	.021*	.012*	.009*	.008*
-65	.453	.106	.037*	.021*	.015*	.014*
-60	.705	.176	.062	.037*	.026*	.023*
-55	1.074	.286	.106	.062	.045*	.040*
-50	1.605	.453	.176	.106	.077	.069
-45	2.358	.705	.286	.176	.130	.117
-40	3.407	1.074	.453	.286	.214	.194
-35	4.847	1.605	.705	.453	.344	.314
-30	6.797	2.358	1.074	.705	.542	.496
-25	9.399	3.407	1.605	1.074	.836	.768
-20	12.830	4.847	2.358	1.605	1.264	1.165

* Indicates doubtful value

TABLE Ic

Density of Water Vapor in Wake Saturated/Ice (gm/m^3)

Temp. of Environment (T_E, °C)	Wake Temp. Minus Initial Environment Temp. — (ΔT, °C)					
	35°C	20°C	10°C	5°C	2°C	1°C
-70	.203	.038	.011	.006	.004	.003
-65	.338	.068	.021	.011	.007	.006
-60	.552	.119	.038	.021	.014	.013
-55	.884	.203	.068	.038	.027	.024
-50	1.387	.338	.119	.068	.048	.043
-45	2.139	.552	.203	.119	.086	.077
-40	3.246	.884	.338	.203	.148	.133
-35	4.847	1.387	.552	.338	.250	.225
-30	6.797	2.139	.884	.552	.413	.374
-25	9.399	3.246	1.387	.884	.668	.608
-20	12.830	4.847	2.139	1.387	1.060	.968

TABLE IIa

Density of Water Vapor Required for Wake Saturated/Water (gm/m^3), for Various Relative Humidities

RH_E = 100 Percent

Temp. of Environment (T_E, °C)	Wake Temp. Minus Initial Environment Temp. — (ΔT, °C)					
	35°C	20°C	10°C	5°C	2°C	1°C
-70	.280	.056	.015	.006	.003	.002
-65	.441	.094	.025	.009	.003	.002
-60	.684	.155	.041	.016	.005	.002
-55	1.037	.249	.069	.025	.008	.003
-50	1.543	.391	.114	.044	.015	.007
-45	2.252	.599	.180	.070	.024	.009
-40	3.231	.898	.277	.110	.038	.018
-35	4.561	1.319	.419	.167	.058	.028
-30	6.344	1.905	.621	.252	.089	.043
-25	8.694	2.702	.900	.369	.131	.063
-20	11.756	3.773	1.284	.531	.190	.091

TABLE IIa (Cont'd)

Density of Water Vapor Required for Wake Saturated/Water (gm/m^3) for Various Relative Humidities

RH_E = 90 Percent

Temp. of Environment (T_E, °C)	Wake Temp. Minus Initial Environment Temp. — (ΔT, °C)					
	35°C	20°C	10°C	5°C	2°C	1°C
-70	.281	.057	.016	.007	.004	.003
-65	.442	.095	.026	.010	.004	.003
-60	.686	.157	.043	.018	.007	.004
-55	1.041	.253	.073	.029	.012	.007
-50	1.549	.397	.120	.050	.021	.013
-45	2.263	.610	.191	.081	.035	.022
-40	3.249	.916	.295	.128	.056	.036
-35	4.590	1.348	.448	.196	.087	.057
-30	6.391	1.952	.668	.299	.136	.090
-25	8.765	2.773	.971	.440	.202	.134
-20	11.864	3.881	1.392	.639	.298	.199

RH_E = 60 Percent

-70	.282	.058	.017	.008	.005	.004
-65	.446	.099	.030	.014	.008	.007
-60	.692	.163	.049	.024	.013	.010
-55	1.052	.264	.084	.040	.023	.018
-50	1.568	.416	.139	.069	.040	.032
-45	2.294	.641	.222	.112	.066	.053
-40	3.301	.968	.347	.180	.108	.088
-35	4.675	1.433	.533	.281	.172	.142
-30	6.525	2.086	.602	.433	.270	.224
-25	8.976	2.984	1.182	.651	.413	.345
-20	12.186	4.203	1.714	.961	.620	.521

TABLE IIa (Cont'd)

Density of Water Vapor Required for Wake Saturated/Water (gm/m^3)
for Various Relative Humidities

RH_E = 0 Percent

Temp. of Environment (T_E, °C)	Wake Temp. Minus Initial Environment Temp. — (ΔT, °C)					
	35°C	20°C	10°C	5°C	2°C	1°C
-70	.286	.062	.021	.012	.009	.008
-65	.453	.106	.037	.021	.015	.014
-60	.705	.176	.062	.037	.026	.023
-55	1.074	.286	.106	.062	.045	.040
-50	1.605	.453	.176	.106	.077	.069
-45	2.358	.705	.286	.176	.130	.117
-40	3.407	1.074	.453	.286	.214	.194
-35	4.847	1.605	.705	.453	.344	.314
-30	6.797	2.358	1.074	.705	.542	.496
-25	9.399	3.407	1.605	1.074	.836	.768
-20	12.830	4.847	2.358	1.605	1.264	1.165

TABLE IIb

Density of Water Vapor Required for Wake Saturated/Ice (gm/m^3)
for Various Relative Humidities

RH_E = 100 Percent

Temp. of Environment (T_E, °C)	Wake Temp. Minus Initial Environment Temp. — (ΔT, °C)					
	35°C	20°C	10°C	5°C	2°C	1°C
-70	.197	.032	.005	.000	-.002	-.003
-65	.326	.056	.009	-.001	-.005	-.006
-60	.531	.098	.017	.000	-.007	-.008
-55	.847	.166	.031	.001	-.010	-.013
-50	1.325	.276	.057	.006	-.014	-.019
-45	2.033	.446	.097	.013	-.020	-.029
-40	3.070	.708	.162	.027	-.028	-.043
-35	4.561	1.101	.266	.052	-.036	-.061
-30	6.344	1.686	.431	.099	-.040	-.079
-25	8.694	2.541	.682	.179	-.037	-.097
-20	11.756	3.773	1.065	.313	-.014	-.106

TABLE IIb (Cont'd)

Density of Water Vapor Required for Wake Saturated/Ice (gm/m^3) for Various Relative Humidities

RH_E = 90 Percent

Temp. of Environment (T_E, °C)	Wake Temp. Minus Initial Environment Temp. — (ΔT, °C)					
	35°C	20°C	10°C	5°C	2°C	1°C
-70	.198	.033	.006	.001	-.001	-.002
-65	.327	.057	.010	.000	-.004	-.005
-60	.533	.100	.019	.002	-.005	-.006
-55	.851	.170	.035	.005	-.006	-.009
-50	1.331	.282	.063	.012	-.008	-.013
-45	2.044	.457	.108	.024	-.009	-.018
-40	3.088	.726	.180	.045	-.010	-.025
-35	4.590	1.130	.295	.081	-.007	-.032
-30	6.391	1.733	.478	.146	-.007	-.032
-25	8.765	2.612	.753	.250	+.034	-.026
-20	11.864	3.881	1.173	.421	.094	.002

RH_E = 60 Percent

	35°C	20°C	10°C	5°C	2°C	1°C
-70	.199	.034	.007	.002	.000	-.001
-65	.331	.061	.014	.004	.000	-.001
-60	.539	.106	.025	.008	.001	.000
-55	.862	.181	.046	.016	.005	.002
-50	1.350	.301	.082	.031	.011	.006
-45	2.075	.488	.139	.055	.022	.013
-40	3.140	.778	.232	.097	.048	.027
-35	4.675	1.215	.380	.166	.078	.053
-30	6.525	1.867	.612	.280	.141	.102
-25	8.976	2.823	.964	.461	.245	.185
-20	12.186	4.203	1.495	.743	.416	.324

TABLE IIb (Cont'd)

Density of Water Vapor Required for Wake Saturated/Ice (gm/m^3) for Various Relative Humidities

RH_E = 0 Percent

Temp. of Environment (T_E, °C)	Wake Temp. Minus Initial Environment Temp. — (ΔT, °C)					
	35°C	20°C	10°C	5°C	2°C	1°C
-70	.203	.038	.011	.006	.004	.003
-65	.338	.068	.021	.011	.007	.006
-60	.552	.119	.038	.021	.014	.013
-55	.884	.203	.068	.038	.027	.024
-50	1.387	.338	.119	.068	.048	.043
-45	2.139	.552	.203	.119	.086	.077
-40	3.246	.884	.338	.203	.148	.133
-35	4.847	1.387	.552	.338	.250	.225
-30	6.797	2.139	.884	.552	.413	.374
-25	9.399	3.246	1.387	.884	.668	.608
-20	12.830	4.847	2.139	1.387	1.060	.968

TABLE IIc

Density of Water Vapor Required for Wake Saturated/Ice (gm/m^3) plus an Ice-Crystal Concentration of .01 gm/m^3, for Various Relative Humidities

RH_E = 100 Percent

Temp. of Environment (T_E, °C)	Wake Temp. Minus Initial Environment Temp. — (ΔT, °C)					
	35°C	20°C	10°C	5°C	2°C	1°C
-70	.207	.042	.015	.010	.008	.007
-65	.336	.066	.019	.009	.005	.004
-60	.541	.108	.027	.010	.003	.002
-55	.857	.176	.041	.011	.000	-.003
-50	1.335	.286	.067	.016	-.004	-.009
-45	2.043	.456	.107	.023	-.010	-.019
-40	3.080	.718	.172	.037	-.018	-.036
-35	4.571	1.111	.276	.062	-.026	-.051
-30	6.354	1.696	.441	.109	-.030	-.069
-25	8.704	2.551	.692	.189	-.027	-.087
-20	11.766	3.783	1.075	.323	-.004	-.096

TABLE IIc (Cont'd)

Density of Water Vapor Required for Wake Saturated/Ice (gm/m^3)
plus an Ice-Crystal Concentration of .01 gm/m^3, for Various
Relative Humidities

RH_E = 90 Percent

Temp. of Environment $(T_E,\ °C)$	Wake Temp. Minus Initial Environment Temp. — $(\Delta T,\ °C)$					
	35°C	20°C	10°C	5°C	2°C	1°C
-70	.208	.043	.016	.011	.009	.008
-65	.337	.067	.020	.010	.006	.005
-60	.543	.110	.029	.012	.005	.004
-55	.861	.180	.045	.015	.004	.001
-50	1.341	.292	.073	.022	.002	-.003
-45	2.054	.467	.118	.034	.001	-.008
-40	3.098	.736	.190	.055	.000	-.015
-35	4.600	1.140	.305	.091	.003	-.022
-30	6.401	1.743	.488	.156	.003	-.022
-25	8.775	2.622	.763	.260	.044	-.016
-20	11.874	3.891	1.183	.431	.104	.012

RH_E = 60 Percent

-70	.209	.044	.017	.012	.010	.009
-65	.341	.071	.024	.014	.010	.009
-60	.549	.116	.035	.018	.011	.010
-55	.882	.191	.056	.026	.015	.012
-50	1.360	.311	.092	.041	.021	.016
-45	2.085	.498	.149	.065	.032	.023
-40	3.150	.788	.242	.107	.058	.037
-35	4.685	1.225	.390	.176	.088	.063
-30	6.535	1.877	.622	.290	.151	.112
-25	8.986	2.833	.974	.471	.255	.195
-20	12.196	4.213	1.505	.753	.426	.334

TABLE IIc (Cont'd)

Density of Water Vapor Required for Wake Saturated/Ice (gm/m^3)
plus an Ice-Crystal Concentration of .01 gm/m^3, for Various
Relative Humidities

RH_E = 0 Percent

Temp. of Environment $(T_E, °C)$	Wake Temp. Minus Initial Environment Temp. — $(\Delta T, °C)$					
	35°C	20°C	10°C	5°C	2°C	1°C
-70	.213	.048	.021	.016	.014	.013
-65	.348	.078	.031	.021	.017	.016
-60	.562	.129	.048	.031	.024	.023
-55	.894	.213	.078	.048	.037	.034
-50	1.397	.348	.129	.078	.058	.053
-45	2.149	.562	.213	.129	.096	.087
-40	3.256	.894	.348	.213	.158	.143
-35	4.857	1.397	.562	.348	.260	.235
-30	6.807	2.149	.894	.562	.423	.384
-25	9.409	3.256	1.397	.894	.678	.618
-20	12.840	4.857	2.149	1.397	1.070	.978

TABLE III

Density of Wake (gm/m³) for Various Temperature Differences Between the Wake Temperature and the Initial Temperature of the Environment

Wake Temperature Minus Initial Temperature of Environment (ΔT) = 35°C

Temp. of Environment	40	50	60	70	80	90	100	200	300	400	500	600	700	800	900	1000
-70	.058	.073	.088	.102	.117	.132	.146	.293	.439	.585	.731	.878	1.024	1.170	1.316	1.463
-65	.057	.072	.086	.100	.115	.129	.143	.286	.430	.573	.716	.860	1.003	1.146	1.290	1.433
-60	.056	.070	.084	.098	.112	.126	.140	.281	.421	.562	.702	.842	.983	1.123	1.264	1.404
-55	–	–	–	–	–	–	.138	.275	.413	.550	.688	.826	.963	1.101	1.238	1.376
-50	–	–	–	–	–	–	.135	.270	.405	.540	.675	.810	.945	1.080	1.214	1.350
-45	–	–	–	–	–	–	.132	.265	.397	.530	.662	.794	.927	1.059	1.192	1.324
-40	–	–	–	–	–	–	.130	.260	.390	.520	.650	.780	.909	1.039	1.169	1.299
-35	–	–	–	–	–	–	.128	.255	.383	.510	.638	.765	.893	1.020	1.148	1.275

Wake Temperature Minus Initial Temperature of Environment (ΔT) = 20°C

Temp. of Environment	40	50	60	70	80	90	100	200	300	400	500	600	700	800	900	1000
-70	.062	.078	.094	.109	.125	.140	.156	.312	.468	.624	.781	.937	1.093	1.249	1.405	1.561
-65	.061	.076	.092	.107	.122	.138	.153	.305	.458	.611	.764	.916	1.069	1.222	1.374	1.527
-60	.060	.075	.090	.105	.120	.134	.149	.299	.448	.598	.747	.896	1.046	1.195	1.345	1.494
-55	.058	.073	.088	.102	.117	.132	.146	.293	.439	.585	.731	.878	1.024	1.170	1.316	1.463
-50	.057	.072	.086	.100	.115	.129	.143	.286	.430	.573	.716	.860	1.003	1.146	1.290	1.433
-45	.056	.070	.084	.098	.112	.126	.140	.281	.421	.562	.702	.842	.983	1.123	1.264	1.404
-40	.055	.069	.083	.096	.110	.124	.138	.275	.413	.550	.688	.826	.963	1.101	1.238	1.376
-35	–	–	–	–	–	–	.135	.270	.405	.540	.675	.810	.945	1.080	1.214	1.350
-30	–	–	–	–	–	–	.132	.265	.397	.530	.662	.794	.927	1.059	1.192	1.324
-25	–	–	–	–	–	–	.130	.260	.390	.520	.650	.780	.909	1.039	1.169	1.299
-20	–	–	–	–	–	–	.128	.255	.383	.510	.638	.765	.893	1.020	1.148	1.275

Wake Temperature Minus Initial Temperature of Environment (ΔT) = 10°C

Temp. of Environment	40	50	60	70	80	90	100	200	300	400	500	600	700	800	900	1000
-70	.065	.082	.098	.114	.131	.147	.163	.327	.490	.654	.817	.981	1.144	1.308	1.471	1.634
-65	.064	.080	.096	.112	.128	.144	.160	.319	.479	.639	.798	.958	1.118	1.278	1.437	1.597
-60	.062	.078	.094	.109	.125	.140	.156	.312	.458	.624	.781	.937	1.093	1.249	1.405	1.561
-55	.061	.076	.092	.107	.122	.138	.153	.305	.458	.611	.764	.916	1.069	1.222	1.374	1.527
-50	.060	.075	.090	.105	.120	.134	.149	.299	.448	.598	.747	.896	1.046	1.195	1.345	1.494
-45	.058	.073	.088	.102	.117	.132	.146	.293	.439	.585	.731	.878	1.024	1.170	1.316	1.463
-40	.057	.072	.086	.100	.115	.129	.143	.286	.430	.573	.716	.860	1.003	1.146	1.290	1.433
-35	–	–	–	–	–	–	.140	.281	.421	.562	.702	.842	.983	1.123	1.264	1.404
-30	–	–	–	–	–	–	.138	.275	.413	.550	.688	.826	.963	1.101	1.238	1.376
-25	–	–	–	–	–	–	.135	.270	.405	.540	.675	.810	.945	1.080	1.214	1.350
-20	–	–	–	–	–	–	.122	.265	.397	.530	.662	.794	.927	1.059	1.192	1.324

Pressure (mb)

TABLE III (Cont'd)

Density of Wake (gm/m³) for Various Temperature Differences Between the Wake Temperature and the Initial Temperature of the Environment

Wake Temperature Minus Initial Temperature of Environment (ΔT) = 5°C

Temp. of Environment	Pressure (mb)															
	40	50	60	70	80	90	100	200	300	400	500	600	700	800	900	1000
-70	.067	.084	.100	.117	.134	.151	.167	.335	.502	.670	.837	1.004	1.172	1.339	1.506	1.674
-65	.065	.082	.098	.114	.131	.147	.163	.327	.490	.654	.817	.981	1.144	1.308	1.471	1.634
-60	.064	.080	.096	.112	.128	.144	.160	.319	.479	.639	.798	.958	1.118	1.278	1.437	1.597
-55	.062	.078	.094	.109	.125	.140	.156	.312	.468	.624	.781	.937	1.093	1.249	1.405	1.561
-50	.061	.076	.092	.107	.122	.137	.153	.305	.458	.611	.764	.916	1.069	1.222	1.374	1.527
-45	.060	.075	.090	.105	.120	.134	.149	.299	.448	.598	.747	.896	1.046	1.195	1.345	1.494
-40	.058	.073	.088	.102	.117	.132	.146	.293	.439	.585	.731	.878	1.024	1.170	1.316	1.463
-35						-	.143	.286	.430	.573	.716	.860	1.003	1.146	1.290	1.433
-30							.140	.281	.421	.562	.702	.842	.983	1.123	1.264	1.404
-25							.138	.275	.413	.550	.688	.826	.963	1.101	1.238	1.376
-20							.135	.270	.405	.540	.675	.810	.945	1.080	1.214	1.350

Wake Temperature Minus Initial Temperature of Environment (ΔT) = 2°C

Temp. of Environment	Pressure (mb)															
	40	50	60	70	80	90	100	200	300	400	500	600	700	800	900	1000
-70	.068	.085	.102	.119	.136	.153	.170	.340	.509	.679	.849	1.019	1.189	1.358	1.528	1.698
-65	.066	.083	.100	.116	.133	.149	.166	.332	.497	.663	.829	.995	1.160	1.326	1.492	1.658
-60	.065	.081	.097	.113	.130	.146	.162	.324	.486	.648	.810	.972	1.133	1.295	1.457	1.619
-55	.063	.079	.095	.111	.127	.142	.158	.316	.475	.633	.791	.949	1.108	1.266	1.424	1.582
-50	.062	.077	.093	.108	.124	.139	.155	.310	.464	.619	.774	.928	1.083	1.238	1.392	1.547
-45	.061	.076	.091	.106	.121	.136	.151	.303	.454	.606	.757	.908	1.060	1.211	1.362	1.514
-40	.059	.074	.089	.104	.118	.133	.148	.296	.444	.593	.741	.889	1.037	1.185	1.333	1.482
-35							.145	.290	.435	.580	.725	.870	1.015	1.160	1.306	1.451
-30							.142	.284	.426	.568	.710	.853	.995	1.137	1.279	1.421
-25							.139	.278	.418	.557	.696	.836	.975	1.114	1.253	1.393
-20							.136	.273	.410	.546	.683	.819	.956	1.092	1.229	1.365

Wake Temperature Minus Initial Temperature of Environment (ΔT) = 1°C

Temp. of Environment	Pressure (mb)															
	40	50	60	70	80	90	100	200	300	400	500	600	700	800	900	1000
-70	.068	.085	.102	.119	.136	.154	.171	.341	.512	.683	.853	1.024	1.194	1.365	1.536	1.706
-65	.067	.083	.100	.117	.133	.150	.167	.333	.500	.666	.833	.999	1.166	1.332	1.499	1.666
-60	.065	.081	.098	.114	.130	.146	.163	.325	.488	.651	.813	.976	1.139	1.301	1.464	1.627
-55	.064	.080	.095	.111	.127	.143	.159	.318	.477	.636	.795	.954	1.113	1.272	1.31	1.590
-50	.062	.078	.093	.109	.124	.140	.155	.311	.466	.622	.777	.932	1.088	1.243	1.399	1.554
-45	.061	.076	.091	.106	.122	.137	.152	.304	.456	.608	.760	.912	1.064	1.216	1.368	1.520
-40	.060	.074	.089	.104	.119	.134	.149	.298	.446	.595	.744	.893	1.042	1.190	1.339	1.488
-35							.146	.291	.437	.583	.728	.874	1.020	1.165	1.311	1.457
-30							.143	.285	.428	.571	.713	.856	.999	1.142	1.284	1.427
-25							.140	.280	.420	.559	.699	.839	.979	1.119	1.258	1.398
-20							.137	.274	.411	.548	.685	.822	.960	1.097	1.234	1.371

TABLE IV

Density of Water Vapor Added to Wake by Fuel (gm/m^3) for Various Temperature Differences
Between the Wake Temperature and the Initial Temperature of the Environment

Wake Temperature Minus Initial Temperature of Environment (ΔT) = 35°C

Temp. of Environment							Pressure (mb)									
	40	50	60	70	80	90	100	200	300	400	500	600	700	800	900	1000
-70	.068	.086	.103	.120	.138	.155	.172	.345	.516	.688	.860	1.03	1.20	1.38	1.55	1.72
-65	.067	.085	.101	.118	.135	.152	.168	.337	.506	.674	.841	1.01	1.18	1.35	1.52	1.69
-60	.066	.082	.099	.115	.132	.148	.165	.330	.495	.661	.826	.990	1.16	1.32	1.49	1.65
-55	—	—	—	—	—	—	.162	.324	.486	.646	.809	.971	1.13	1.29	1.45	1.62
-50	—	—	—	—	—	—	.159	.318	.476	.635	.794	.953	1.11	1.27	1.43	1.59
-45	—	—	—	—	—	—	.155	.312	.467	.623	.779	.933	1.09	1.25	1.40	1.56
-40	—	—	—	—	—	—	.153	.306	.459	.611	.765	.916	1.07	1.23	1.37	1.53
-35	—	—	—	—	—	—	.151	.300	.450	.600	.750	.900	1.05	1.20	1.35	1.50

Wake Temperature Minus Initial Temperature of Environment (ΔT) = 20°C

Temp. of Environment							Pressure (mb)									
	40	50	60	70	80	90	100	200	300	400	500	600	700	800	900	1000
-70	.042	.052	.063	.073	.084	.094	.105	.210	.314	.419	.525	.630	.734	.839	.944	1.049
-65	.041	.051	.062	.072	.082	.093	.103	.205	.308	.411	.513	.616	.718	.821	.923	1.026
-60	.040	.050	.060	.071	.081	.090	.100	.201	.301	.402	.502	.602	.703	.800	.904	1.004
-55	.039	.049	.059	.069	.079	.089	.098	.197	.295	.393	.491	.590	.688	.786	.884	.983
-50	.038	.048	.058	.068	.077	.087	.096	.192	.289	.385	.481	.578	.674	.770	.867	.963
-45	.038	.047	.056	.065	.075	.085	.094	.189	.283	.378	.472	.566	.661	.755	.849	.943
-40	.037	.046	.056	.065	.074	.083	.093	.185	.278	.370	.462	.555	.647	.740	.832	.925
-35	—	—	—	—	—	—	.091	.181	.272	.363	.454	.544	.635	.726	.816	.907
-30	—	—	—	—	—	—	.089	.178	.267	.356	.445	.534	.623	.712	.801	.890
-25	—	—	—	—	—	—	.088	.175	.262	.349	.437	.524	.611	.698	.786	.873
-20	—	—	—	—	—	—	.086	.171	.257	.343	.429	.514	.600	.685	.771	.857

Wake Temperature Minus Initial Temperature of Environment (ΔT) = 10°C

Temp. of Environment							Pressure (mb)									
	40	50	60	70	80	90	100	200	300	400	500	600	700	800	900	1000
-70	.022	.028	.033	.038	.044	.049	.055	.110	.165	.220	.275	.330	.384	.439	.494	.549
-65	.022	.027	.032	.038	.043	.048	.054	.107	.161	.215	.268	.322	.376	.429	.483	.537
-60	.021	.026	.032	.037	.042	.047	.052	.105	.157	.210	.262	.315	.367	.420	.472	.524
-55	.020	.026	.031	.036	.041	.046	.051	.102	.154	.205	.257	.308	.359	.411	.462	.513
-50	.020	.025	.030	.035	.040	.045	.050	.100	.151	.201	.251	.301	.351	.402	.452	.502
-45	.019	.025	.030	.034	.039	.044	.049	.098	.148	.197	.246	.295	.344	.393	.442	.493
-40	.019	.024	.029	.034	.039	.043	.048	.096	.144	.193	.241	.289	.337	.385	.433	.481
-35	—	—	—	—	—	—	.047	.094	.141	.189	.236	.283	.330	.377	.425	.472
-30	—	—	—	—	—	—	.046	.092	.139	.185	.231	.278	.324	.370	.416	.462
-25	—	—	—	—	—	—	.045	.091	.136	.181	.227	.272	.318	.363	.408	.454
-20	—	—	—	—	—	—	.044	.089	.133	.178	.222	.267	.311	.356	.401	.445

TABLE IV (Cont'd)

Density of Water Vapor Added to Wake by Fuel (gm/m^3) for Various Temperature Differences Between the Wake Temperature and the Initial Temperature of the Environment

Wake Temperature Minus Initial Temperature of Environment $(\Delta T) = 5°C$

Temp. of Environment	1000	900	800	700	600	500	400	300	200	100	90	80	70	60	50	40
-70	.281	.253	.225	.197	.169	.141	.113	.084	.056	.028	.025	.023	.020	.017	.014	.011
-65	.275	.247	.220	.192	.165	.137	.110	.082	.055	.027	.025	.022	.019	.016	.013	.011
-60	.268	.241	.215	.188	.161	.134	.107	.080	.054	.027	.024	.022	.019	.016	.013	.011
-55	.262	.236	.210	.184	.157	.131	.105	.079	.052	.026	.024	.021	.018	.016	.013	.010
-50	.257	.231	.205	.180	.154	.128	.103	.077	.051	.026	.023	.020	.018	.015	.013	.010
-45	.251	.226	.201	.176	.151	.125	.100	.075	.050	.025	.023	.020	.018	.015	.013	.010
-40	.246	.221	.197	.172	.148	.123	.098	.074	.049	.025	.022	.020	.017	.015	.012	.010
-35	.241	.217	.193	.169	.144	.120	.096	.072	.048	.024	—	—	—	—	—	—
-30	.236	.212	.189	.165	.141	.118	.094	.071	.047	.024	—	—	—	—	—	—
-25	.231	.208	.185	.162	.139	.116	.092	.069	.046	.023	—	—	—	—	—	—
-20	.227	.204	.181	.159	.136	.113	.091	.068	.045	.023	—	—	—	—	—	—

Wake Temperature Minus Initial Temperature of Environment $(\Delta T) = 2°C$

Temp. of Environment	1000	900	800	700	600	500	400	300	200	100	90	80	70	60	50	40
-70	.114	.103	.091	.080	.068	.057	.046	.034	.023	.011	.010	.009	.008	.007	.006	.005
-65	.111	.100	.089	.078	.067	.056	.045	.033	.022	.011	.010	.009	.008	.007	.006	.004
-60	.109	.098	.087	.076	.065	.054	.044	.033	.022	.011	.010	.009	.008	.007	.005	.004
-55	.106	.096	.085	.074	.064	.053	.043	.032	.021	.011	.010	.009	.007	.006	.005	.004
-50	.104	.094	.083	.073	.062	.053	.042	.031	.021	.010	.009	.008	.007	.006	.005	.004
-45	.102	.092	.081	.071	.061	.051	.041	.031	.020	.010	.009	.008	.007	.006	.005	.004
-40	.100	.090	.080	.070	.060	.050	.040	.030	.020	.010	.009	.008	.007	.006	.005	.004
-35	.098	.088	.078	.068	.058	.049	.039	.029	.019	.010	—	—	—	—	—	—
-30	.095	.086	.076	.067	.057	.048	.038	.029	.019	.010	—	—	—	—	—	—
-25	.094	.084	.075	.066	.056	.047	.037	.028	.019	.009	—	—	—	—	—	—
-20	.092	.083	.073	.064	.055	.046	.037	.028	.018	.009	—	—	—	—	—	—

Wake Temperature Minus Initial Temperature of Environment $(\Delta T) = 1°C$

Temp. of Environment	1000	900	800	700	600	500	400	300	200	100	90	80	70	60	50	40
-70	.057	.052	.046	.040	.034	.029	.023	.017	.011	.006	.005	.005	.004	.003	.003	.002
-65	.056	.050	.045	.039	.034	.028	.022	.017	.011	.006	.005	.004	.004	.003	.003	.002
-60	.055	.049	.044	.038	.033	.027	.022	.016	.011	.005	.005	.004	.004	.003	.003	.002
-55	.053	.048	.043	.037	.032	.026	.021	.016	.011	.005	.005	.004	.004	.003	.003	.002
-50	.052	.047	.042	.037	.031	.026	.021	.016	.010	.005	.005	.004	.004	.003	.003	.002
-45	.051	.046	.041	.036	.031	.026	.020	.015	.010	.005	.005	.004	.004	.003	.003	.002
-40	.050	.045	.040	.035	.030	.025	.020	.015	.010	.005	.005	.004	.003	.003	.002	.002
-35	.049	.044	.039	.034	.029	.024	.020	.015	.010	.005	—	—	—	—	—	—
-30	.048	.043	.038	.034	.029	.024	.019	.014	.010	.005	—	—	—	—	—	—
-25	.047	.042	.038	.033	.028	.023	.019	.014	.009	.005	—	—	—	—	—	—
-20	.046	.041	.037	.032	.028	.023	.018	.014	.009	.005	—	—	—	—	—	—

Pressure (mb)

TABLE Va

Critical Temperature for Formation of Wake Saturated Water (°C) for Various Temperature Differences Between the Wake Temperature and the Initial Temperature of the Environment

Wake Temperature Minus Initial Temperature of Environment (ΔT) = 35°C

Pressure (mb)

Relative Humidity of Environment	1000	900	800	700	600	500	400	300	200	100	90	80	70	60	50	40
100	-49.7	-50.9	-52.3	-54.0	-55.8	-57.8	-60.3	-63.5	-67.8	-70	<-70	<-70	<-70	<-70	<-70	<-70
90	-49.9	-51.1	-52.5	-54.2	-56.0	-58.0	-60.4	-63.6	-67.9	-70	<-70	<-70	<-70	<-70	<-70	<-70
60	-50.1	-51.4	-52.8	-54.4	-56.2	-58.2	-60.6	-63.7	-68.0	-70	<-70	<-70	<-70	<-70	<-70	<-70
0	-50.3	-51.6	-53.0	-54.6	-56.4	-58.4	-60.8	-63.9	-68.2	-70	<-70	<-70	<-70	<-70	<-70	<-70

Wake Temperature Minus Initial Temperature of Environment (ΔT) = 20°C

Relative Humidity of Environment	1000	900	800	700	600	500	400	300	200	100	90	80	70	60	50	40
100	-39.5	-40.9	-42.2	-43.8	-45.3	-47.7	-50.2	-53.2	-57.5	-64.2	-65.1	-66.2	-67.4	-68.9	<-70	<-70
90	-39.6	-41.3	-42.7	-44.2	-45.7	-48.0	-50.5	-53.4	-57.7	-64.4	-65.4	-66.5	-67.7	-69.1	<-70	<-70
60	-40.6	-41.9	-43.2	-44.8	-46.3	-48.5	-50.9	-53.9	-58.0	-64.6	-65.7	-66.8	-68.0	-69.3	<-70	<-70
0	-41.7	-42.9	-44.2	-45.7	-47.2	-49.5	-51.8	-54.7	-58.7	-65.2	-66.3	-67.2	-68.3	-69.6	<-70	<-70

Wake Temperature Minus Initial Temperature of Environment (ΔT) = 10°C

Relative Humidity of Environment	1000	900	800	700	600	500	400	300	200	100	90	80	70	60	50	40
100	-33.3	-34.7	-36.1	-37.6	-39.3	-41.4	-43.9	-47.0	-51.2	-57.9	-58.9	-60.0	-61.1	-62.6	-64.3	-66.5
90	-34.3	-35.6	-37.0	-38.6	-40.2	-42.2	-44.7	-47.7	-51.8	-58.2	-59.2	-60.3	-61.5	-63.0	-64.7	-66.9
60	-36.3	-37.6	-38.8	-40.2	-42.0	-44.0	-46.3	-49.2	-53.2	-59.6	-60.4	-61.4	-62.8	-64.0	-65.7	-67.8
0	-39.4	-40.5	-41.7	-43.0	-44.7	-46.4	-48.6	-51.4	-55.2	-61.6	-62.4	-63.4	-64.7	-66.0	-67.6	-69.7

Wake Temperature Minus Initial Temperature of Environment (ΔT) = 5°C

Relative Humidity of Environment	1000	900	800	700	600	500	400	300	200	100	90	80	70	60	50	40
100	-30.8	-32.0	-33.3	-34.8	-36.6	-38.7	-41.2	-44.2	-48.5	-55.1	-56.2	-57.1	-58.5	-59.9	-61.6	-63.6
90	-32.8	-34.0	-35.3	-36.8	-38.6	-40.5	-42.9	-45.7	-49.8	-56.2	-57.3	-58.2	-59.5	-61.0	-62.6	-64.6
60	-36.7	-37.8	-39.0	-40.4	-42.0	-43.9	-46.0	-48.9	-52.8	-58.9	-60.0	-60.8	-62.0	-63.4	-65.0	-67.0
0	-41.5	-42.5	-43.6	-44.9	-46.4	-48.1	-50.3	-52.9	-56.6	-62.8	-63.7	-64.6	-65.7	-67.0	-68.6	<-70

Wake Temperature Minus Initial Temperature of Environment (ΔT) = 2°C

Relative Humidity of Environment	1000	900	800	700	600	500	400	300	200	100	90	80	70	60	50	40
100	-29.0	-30.3	-31.7	-33.1	-35.0	-37.0	-39.3	-42.5	-46.6	-53.3	-54.5	-55.6	-56.7	-58.0	-59.7	-51.8
90	-33.8	-35.0	-36.2	-37.8	-39.2	-41.3	-43.5	-46.2	-50.0	-56.0	-56.9	-58.0	-59.0	-60.2	-61.8	-63.9
60	-40.8	-41.8	-43.0	-44.4	-45.9	-47.7	-49.7	-52.2	-56.0	-62.1	-63.1	-64.0	-65.1	-66.4	-67.9	-70
0	-47.2	-48.2	-49.4	-50.5	-51.8	-53.5	-55.3	-58.0	-61.5	-67.7	-68.7	-69.5	-70.3	<-70	<-70	<-70

Wake Temperature Minus Initial Temperature of Environment (ΔT) = 1°C

Relative Humidity of Environment	1000	900	800	700	600	500	400	300	200	100	90	80	70	60	50	40
100	-28.6	-30.0	-31.4	-32.7	-34.4	-36.5	-38.9	-41.8	-45.9	-52.9	-54.0	-55.0	-56.2	-57.6	-59.6	-61.3
90	-36.9	-38.0	-39.0	-40.3	-41.7	-43.5	-45.9	-48.0	-51.6	-57.5	-58.5	-59.5	-60.6	-61.9	-63.6	-65.2
60	-45.4	-46.3	-47.4	-48.7	-50.2	-51.8	-53.7	-56.2	-59.6	-65.0	-66.0	-67.0	-68.0	-69.1	-70	-70
0	-52.6	-53.6	-54.5	-55.7	-57.0	-58.6	-60.5	-63.2	-66.8	-73.0	<-70	<-70	<-70	<-70	<-70	<-70

TABLE Vb

Critical Temperature for Formation of Wake Saturated/Ice (°C) for Various Temperature Differences Between the Wake Temperature and the Initial Temperature of the Environment

Wake Temperature Minus Initial Temperature of Environment (ΔT) = 35°C

Relative Humidity of Environment	Pressure (mb)									
	1000	900	800	700	600	500	400	300	200	100
100	-48.1	-49.2	-50.6	-52.0	-53.7	-55.6	-57.8	-60.7	-64.7	-70
90	-48.2	-49.4	-50.8	-52.2	-53.9	-55.7	-57.9	-60.9	-64.8	-70
60	-48.3	-49.6	-50.9	-52.4	-54.0	-55.8	-58.1	-61.0	-65.0	-70
0	-48.5	-49.7	-51.0	-52.5	-54.1	-56.0	-58.2	-61.2	-65.1	-70

Wake Temperature Minus Initial Temperature of Environment (ΔT) = 20°C

Relative Humidity of Environment	1000	900	800	700	600	500	400	300	200	100
100	-37.1	-38.5	-39.8	-41.0	-42.7	-44.4	-46.7	-49.6	-53.6	-59.7
90	-37.6	-38.8	-40.2	-41.7	-43.1	-44.9	-47.2	-49.9	-54.0	-59.9
60	-38.3	-39.5	-40.8	-42.1	-43.7	-45.4	-47.8	-50.6	-54.7	-60.7
0	-39.6	-40.8	-42.1	-43.3	-44.8	-46.7	-48.9	-51.7	-55.5	-61.6

Wake Temperature Minus Initial Temperature of Environment (ΔT) = 10°C

Relative Humidity of Environment	1000	900	800	700	600	500	400	300	200	100
100	-29.2	-30.2	-31.5	-32.8	-34.3	-36.1	-38.3	-40.0	-45.0	-51.2
90	-30.3	-31.4	-32.6	-33.8	-35.3	-37.0	-39.3	-42.0	-45.8	-51.8
60	-32.9	-33.9	-35.1	-36.4	-37.9	-39.7	-41.8	-44.6	-48.3	-54.2
0	-36.7	-37.6	-38.8	-40.0	-41.5	-43.2	-45.4	-48.0	-51.4	-57.4

Wake Temperature Minus Initial Temperature of Environment (ΔT) = 5°C

Relative Humidity of Environment	1000	900	800	700	600	500	400	300	200	100
100	-22.8	-23.7	-24.7	-25.8	-27.0	-28.5	-30.3	-32.4	-35.7	-40.8
90	-25.9	-26.8	-27.8	-28.9	-30.3	-31.7	-33.7	-36.0	-39.5	-44.7
60	-31.8	-32.7	-33.8	-35.0	-36.3	-38.0	-40.0	-42.3	-45.9	-51.5
0	-38.2	-39.2	-40.3	-41.5	-42.9	-44.6	-46.4	-48.8	-52.3	-58.1

Wake Temperature Minus Initial Temperature of Environment (ΔT) = 2°C

Relative Humidity of Environment	1000	900	800	700	600	500	400	300	200	100
100	>-20	>-20	>-20	>-20	>-20	>-20	>-20	>-20	>-20	>-20
90	-19.9	-20.7	-21.5	-22.3	-23.0	-24.0	-24.8	-25.6	-26.5	-27.4
60	-33.9	-34.7	-35.7	-36.7	-38.0	-39.3	-41.0	-43.0	-45.8	-50.3
0	-43.3	-44.2	-45.5	-46.5	-47.9	-49.4	-51.3	-53.5	-56.7	-62.0

Wake Temperature Minus Initial Temperature of Environment (ΔT) = 1°C

Relative Humidity of Environment	1000	900	800	700	600	500	400	300	200	100
100	>-20	>-20	>-20	>-20	>-20	>-20	>-20	>-20	>-20	>-20
90	>-20	>-20	>-20	>-20	>-20	>-20	>-20	>-20	>-20	>-20
60	-35.6	-36.4	-37.3	-38.3	-39.4	-40.7	-42.1	-44.0	-46.4	-50.7
0	-48.6	-49.5	-50.4	-51.6	-52.9	-54.4	-56.2	-58.5	-61.3	-65.7

TABLE Vc

Critical Temperature for Formation of Wake Saturated/Ice Plus an Ice-Crystal Concentration of .01 gm/m^3 (°C) for Various Temperature Differences Between the Wake Temperature and the Initial Temperature of the Environment

Wake Temperature Minus Initial Temperature of Environment (ΔT) = 35°C

Relative Humidity of Environment	1000	900	800	700	600	500	400	300	200	100	90	80	70	60	50	40
100	-48.1	-49.2	-50.5	-51.9	-53.7	-55.7	-58.0	-60.9	-65.0	-70	<-70	<-70	<-70	<-70	<-70	<-70
90	-48.3	-49.4	-50.7	-52.1	-53.9	-55.9	-58.1	-61.0	-65.1	-70	<-70	<-70	<-70	<-70	<-70	<-70
60	-48.5	-49.6	-50.9	-52.3	-54.0	-56.0	-58.2	-61.2	-65.2	-70	<-70	<-70	<-70	<-70	<-70	<-70
0	-48.7	-49.8	-51.0	-52.5	-54.1	-56.1	-58.3	-61.3	-65.3	-70	<-70	<-70	<-70	<-70	<-70	<-70

Wake Temperature Minus Initial Temperature of Environment (ΔT) = 20°C

Relative Humidity of Environment	1000	900	800	700	600	500	400	300	200	100	90	80	70	60	50	40
100	-37.2	-38.3	-39.9	-41.0	-42.7	-44.6	-46.9	-50.0	-54.1	-60.7	-61.7	-62.8	-64.0	-65.7	-67.5	-69.8
90	-37.7	-38.8	-40.2	-41.5	-43.0	-44.9	-47.2	-50.3	-54.3	-61.0	-61.9	-63.1	-64.3	-65.9	-67.7	<-70
60	-38.3	-39.5	-40.9	-42.0	-43.6	-45.5	-47.7	-50.6	-54.7	-61.4	-62.3	-63.5	-64.8	-66.3	-68.1	<-70
0	-39.5	-40.7	-42.0	-43.3	-44.8	-46.7	-48.8	-50.8	-55.7	-62.3	-63.2	-64.4	-65.7	-67.1	-69.0	<-70

Wake Temperature Minus Initial Temperature of Environment (ΔT) = 10°C

Relative Humidity of Environment	1000	900	800	700	600	500	400	300	200	100	90	80	70	60	50	40
100	-29.4	-30.4	-31.8	-33.0	-34.6	-36.5	-38.8	-41.7	-45.9	-52.7	-53.8	-55.0	-56.3	-58.0	-60.2	-63.3
90	-30.6	-31.7	-33.0	-34.3	-35.7	-37.7	-39.8	-42.7	-46.8	-53.7	-54.8	-56.0	-57.3	-59.0	-61.0	-64.1
60	-33.0	-34.0	-35.3	-36.7	-38.2	-40.0	-42.2	-45.2	-49.2	-55.8	-56.9	-58.0	-59.4	-61.2	-63.1	-66.0
0	-36.5	-37.7	-38.8	-40.2	-41.7	-43.5	-45.8	-48.6	-52.3	-59.0	-60.1	-61.3	-62.7	-64.3	-66.4	-69.0

Wake Temperature Minus Initial Temperature of Environment (ΔT) = 5°C

Relative Humidity of Environment	1000	900	800	700	600	500	400	300	200	100	90	80	70	60	50	40
100	-23.3	-24.1	-25.2	-26.2	-27.7	-29.3	-31.5	-33.9	-37.6	-44.2	-45.8	-46.7	-48.2	-50.0	-52.3	-55.7
90	-26.2	-27.1	-28.3	-29.4	-30.9	-32.0	-34.8	-37.3	-41.2	-48.3	-49.7	-50.9	-52.3	-54.2	-57.1	-61.7
60	-32.1	-33.1	-34.3	-35.6	-37.0	-39.0	-41.1	-43.7	-47.8	-55.0	-56.3	-57.5	-59.3	-61.9	-65.9	<-70
0	-38.7	-39.7	-40.7	-42.0	-43.4	-45.3	-47.5	-50.1	-54.2	-62.0	-63.2	-64.8	-66.7	-69.0	<-70	<-70

Wake Temperature Minus Initial Temperature of Environment (ΔT) = 2°C

Relative Humidity of Environment	1000	900	800	700	600	500	400	300	200	100	90	80	70	60	50	40
100	>-20	>-20	>-20	>-20	>-20	>-20	>-20	>-20	>-20	>-20	>-20	>-20	>-20	>-20	>-20	>-20
90	>-20	>-20	>-20	>-20	>-20	>-20	>-20	>-20	>-20	-20.6	-21.0	-21.5	-22.2	-23.3	-24.5	-27.0
60	-34.2	-35.1	-36.2	-37.4	-38.8	-40.3	-42.6	-45.4	-50.0	-61.0	*	*	*	*	*	*
0	-44.6	-45.7	-46.7	-48.0	-49.5	-51.3	-53.4	-56.6	-61.1	-	*	*	*	*	*	*

Alternate values for ΔT = 2°C ⟶

Relative Humidity of Environment	100	90	80	70	60	50	40
100	-70	-70	-70	-70	-68.6	-66.8	-64.2
90	-70	-70	-70	-68.5	-66.4	-63.3	-58.0
60	*	*	*	*	*	*	*
0	*	*	*	*	*	*	*

Pressure (mb)

* Never reaches critical value.

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TABLE Vc (Cont'd)

January 1957

Critical Temperature for Formation of Wake Saturated/Ice Plus an Ice-Crystal Concentration of .01 gm/m³ (°C) for Various Temperature Differences Between the Wake Temperature and the Initial Temperature of the Environment

Wake Temperature Minus Initial Temperature of Environment (ΔT) = 1°C

Relative Humidity of Environment	Pressure (mb) 1000	900	800	700	600	500	400	300	200	100	90	80	70	60	50	40
100	>-20	>-20	>-20	>-20	>-20	>-20	>-20	>-20	>-20	>-20	>-20	>-20	>-20	>-20	>-20	>-20
90	>-20	>-20	>-20	>-20	>-20	>-20	>-20	>-20	>-20.4	-21.0	-21.2	-21.3	-21.5	-21.7	-21.9	-22.1
60	-37.0	-37.9	-38.9	-40.2	-41.8	-43.7	-46.4	-50.3	-58.5	-	*	*	*	*	*	*
0	-50.0	-51.0	-52.3	-53.7	-55.5	-57.7	-60.7	-64.9		-	*	*	*	*	*	*

Alternate values for ΔT = 1°C →

	100	90	80	70	60	50	40
100	-68.4	-66.6	-65.6	-64.3	-63.2	-61.8	-60.3
90	-66.2	-63.6	-62.2	-60.8	-59.7	-58.3	-57.2
60	*	*	*	*	*	*	*
0	*	*	*	*	*	*	*

* Never reaches critical value.

TABLE VI

Comparison of Seasonal and Annual Contrail Probability

95% Probability

Pressure (mb)	Temperature (°C) Winter	Spring	Summer	Autumn	Annual
150	-61.2	-60.6	-59.2	-60.1	-60.6
175	-58.9	-59.0	-58.0	-58.9	-58.8
200	-58.3	-56.5	-58.0	-59.2	-58.5
250	-57.0	-57.8	-55.7	-	-58.1
300	-53.9	-	-	-	-55.6
350	-	-	-	-	-

90% Probability

Pressure (mb)	Temperature (°C) Winter	Spring	Summer	Autumn	Annual
150	-60.0	-59.5	-58.3	-59.2	-59.3
175	-58.9	-57.7	-57.0	-58.0	-57.4
200	-56.7	-56.0	-57.5	-58.0	-56.6
250	-55.0	-56.0	-55.4	-	-56.4
300	-53.6	-54.7	-	-	-54.2
350	-51.7	-	-	-	-49.9

75% Probability

Pressure (mb)	Temperature (°C) Winter	Spring	Summer	Autumn	Annual
150	-57.5	-56.5	-56.7	-57.8	-57.2
175	-55.5	-55.5	-55.3	-56.3	-55.2
200	-54.2	-54.0	-55.5	-55.9	-54.8
250	-52.5	-54.1	-54.3	-54.6	-53.6
300	-51.3	-53.0	-	-	-53.0
350	-49.5	-51.0	-	-	-49.4

50% Probability

Pressure (mb)	Temperature (°C) Winter	Spring	Summer	Autumn	Annual
150	-56.5	-53.5	-55.2	-56.2	-55.5
175	-53.7	-53.3	-54.0	-54.3	-53.4
200	-52.4	-53.0	-53.5	-53.5	-53.2
250	-51.2	-53.0	-52.8	-52.5	-52.1
300	-50.3	-51.0	-	-	-50.5
350	-48.7	-50.3	-	-	-49.0

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TABLE VI (Cont'd)

Comparison of Seasonal and Annual Contrail Probability

25% Probability

Pressure (mb)	Temperature (°C)				
	Winter	Spring	Summer	Autumn	Annual
150	-55.4	-51.5	-54.3	-54.5	-53.6
175	-49.5	-50.5	-52.0	-52.2	-51.4
200	-50.1	-50.0	-51.0	-51.2	-50.8
250	-48.8	-49.5	-50.5	-50.6	-49.8
300	-48.4	-49.0	-	-49.3	-48.8
350	-47.5	-49.0	-	-	-48.0

10% Probability

Pressure (mb)	Winter	Spring	Summer	Autumn	Annual
150	-54.5	-50.0	-52.3	-	-51.5
175	-50.6	-48.3	-50.5	-50.8	-49.6
200	-48.3	-47.3	-48.8	-49.2	-48.5
250	-46.5	-47.0	-47.4	-47.7	-47.0
300	-45.8	-46.7	-46.7	-46.5	-46.4
350	-45.5	-46.5	-	-	-45.8

5% Probability

Pressure (mb)	Winter	Spring	Summer	Autumn	Annual
150	-54.3	-	-51.9	-	-50.6
175	-49.6	-	-49.6	-49.8	-48.5
200	-48.0	-47.0	-47.7	-48.2	-47.1
250	-46.0	-46.2	-45.2	-46.2	-45.1
300	-44.0	-45.3	-	-45.1	-44.3
350	-43.0	-44.3	-	-43.2	-43.7

TABLE VII

Comparison of Contrail Probability for the North (N) and South (S)

Temperature (°C)

Probability Percent	Area	Pressure (mb)				
		150	175	200	250	300
95	N	-61.3	-59.2	-59.0	-	-
	S	-60.0	-58.6	-58.2	-	-
90	N	-60.1	-57.8	-57.6	-56.9	-
	S	-58.9	-57.5	-57.1	-56.3	-
75	N	-57.8	-55.2	-55.1	-53.6	-
	S	-57.3	-55.8	-55.1	-54.0	-
50	N	-55.3	-53.2	-53.0	-51.9	-50.4
	S	-56.2	-54.2	-53.0	-52.0	-51.3
25	N	-	-51.6	-50.4	-49.7	-48.7
	S	-	-52.1	-50.4	-50.0	-49.8
10	N	-	-49.6	-48.3	-46.6	-46.2
	S	-	-50.3	-47.6	-47.5	-47.5
5	N	-	-	-	-44.8	-44.0
	S	-	-	-	-46.0	-45.4

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